Humidity and mechanical properties of onion skins


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Received 7 December 1999; accepted 20 April 2000

Abstract

Strength, stiffness, strain at fracture and moisture content of onion skins were measured after incubation at a range of humidities. Higher relative humidity (RH) resulted in skins which had greater moisture content, were stronger in multi-directional tests and which were less stiff. In uni-directional tests, skins incubated at higher RH had extended more at fracture than those incubated at lower humidity, but were no stronger. Skins exposed to 95% RH were about twice as resistant to breaking in multi-directional testing as those exposed to 16% RH. This effect seemed to result from a much greater ability to extend before fracture occurred. The implications for skin conditioning of stored onion bulbs are discussed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Onion; Bulb; Quality; Skin; Humidity; Mechanics; Strength; Stiffness; Failure stress; Failure strain

1. Introduction

The appearance of onions is an important component of consumers’ perception of quality. High quality bulbs possess entire skins of an acceptable colour and a minimum of blemish. The presence of split skins reduces quality and splitting also leads to skin loss. Skin loss can be of benefit where the outer skin is blemished and its removal would enhance quality. However, partial removal results in bulbs with a scuffed appearance, while unhindered removal of successive skins must ultimately lead to undesirable exposure of fleshy scales. Onion bulbs endure mechanical abuse during postharvest and post-storage handling. Their skins thus need to be capable of resisting this abuse.

Skin splitting and subsequent loss must depend on the mechanical properties of skins. The ease with which skins stretch and tear influences appearance and hence quality. Such variables are likely to be affected by the thickness of skins (Tanaka et al., 1985) as well as their composition and structure.

During curing and storage, outer skins usually experience a net loss of moisture, because initially they contain water and their internal humidity is greater than that of the surrounding atmosphere. However, there comes a point at which water content of this tissue has declined sufficiently for an equilibrium with water vapour pressure of the surrounding atmosphere to be reached (de Matos
et al., 1997). At this point, moisture will be adsorbed or desorbed from the air, depending on vapour pressure deficit in the air and the air-skin temperature difference (Thamizharasari and Narasimham, 1991).

It is of considerable practical importance to determine how such humidity-induced changes in moisture content of skins affect their strength and stiffness, as this may influence skin splitting and thus bulb quality.

2. Materials and methods

2.1. Burst pressure test

This method measures the capability of skin material to withstand tensile loading irrespective of its orientation. The technique is based on that used for measuring skin strength of tomatoes (Voisey and Lyall, 1965).

Samples of onion skin, 14 mm in diameter, were removed from the equatorial region of bulbs using a cork borer. Skins were placed with their outer epidermis to the atmosphere across an orifice (6.8 mm diameter) of a specially-constructed ‘burst unit’. They were held in place by compression between two ‘O’ rings. The skins thus formed a seal on a chamber inside which the pressure was increased at a rate of 0.1 MPa s\(^{-1}\) using compressed air. Preliminary tests on dry skins indicated that rates between 0.04 and 0.16 MPa s\(^{-1}\) had no effect on failure pressure. A transducer interfaced to a computer recorded changes in pressure within the chamber. Peak pressure was taken as the pressure at which skins fractured. This pressure was recorded as a simple estimate of a skin’s ability to resist breaking. No adjustment was made for thickness of the skin, so the term strength is not used for this feature.

The test does not take long to complete (≈ 60 s). In this time, moisture exchange between skin and atmosphere is small, so measurements were made at ambient room conditions, usually around 20°C and 50% relative humidity (RH), rather than in an humidity-controlled environment.

2.2. Stiffness, strength and strain

This technique estimates stiffness, stress and strain of skins experiencing tensile loading in one direction only. Single-edged, single-bevel blades (Durham-Duplex, type ‘D’) clamped in a special holder were used to cut samples of skin (2 × 35 mm) from the equatorial region of bulbs. The orientation of these samples was along the bulb’s equator, perpendicular to the vascular bundles. The samples were mounted on cards (63 × 15 mm, across the length of a cutout (18 mm long by 6 mm wide) using double-sided clear adhesive tape to attach the ends of the sample to the card (Fig. 1). A layer of single-sided adhesive tape was then applied to sandwich the piece of skin. Both this and the double-sided tape were accurately positioned on marks to ensure a consistent separation of 20 mm. This determined the ‘gauge’ length of the specimens. The supporting card and the adhered ends of each sample of skin were then placed in the pneumatic grips of a materials-testing instrument (Instron), with the edges of the grips closed on to the edges of tape. The tape thus provided support for the skin where the grips closed on it, reducing stress caused by the grips and the likelihood of failure at this point. Card on each side of the hole in the support was then cut carefully with scissors and the sample stretched by the machine at a rate of 1 mm min\(^{-1}\). Skin stiffness was obtained as the slope of load per unit cross-sectional area of skin (stress) versus extension divided by gauge length (strain) for the steepest part of the curve (Young’s modulus). Tension was increased until the sample failed, providing estimates of unidirectional stress (strength) and strain at failure.
Areas of cross-section used to estimate stiffness and strength were calculated from skin thickness measured immediately after humidity treatment and after the skins having been dried. Humidification can lead to increased thickness that is due predominantly to the presence of water. Thickness of dried tissue is more likely to represent the dimensions of structural material present.

2.3. Moisture content

This was determined by weighing a sample of skin immediately after removal from a bulb and then re-weighing after drying for at least 48 h at 90°C. Moisture content was expressed as a percentage of tissue fresh weight.

2.4. Skin thickness

Skin thickness was measured with digital electronic callipers (sensitivity of 0.01 mm). An average of several measurements of each sample was always made, avoiding major vascular bundles. These were therefore estimates of inter-veinal tissue thickness.

2.5. Experiments

In all experiments, only outer, dry skins were used. Underlying moist skins that had never been exposed directly to air and still retained considerable flexibility were deliberately excluded. Skins located next to fleshy scales were not used.

2.5.1. Experiment 1

To monitor the uptake and loss of moisture from onion skins, pieces of skin were incubated in a closed perspex chamber maintained at high RH (close to 100% RH) by added water, after having been transferred from ambient air or after having been dried in silica gel. They were briefly removed from the chamber for weighing and then returned. The experiment was done at \( \approx 20°C \). The time taken for onion skin to attain 50% of its stable weight (\( t_{1/2} \)) when transferred to high humidity was estimated from the slope of the log weight against time for the first five data.

2.5.2. Experiment 2

Forty disks of skin were cut from the outer two dry skins of three mature, cured onion bulbs of unknown source and incubated on filter paper for 3 days in desiccators containing either silica gel (\( \approx 16\% \) RH) or water (\( > 95\% \) RH). Filter paper in the higher humidity became wet. As a result, skins in this experiment were in direct contact with liquid water. Disks from the same skins were allocated equally to the two humidities (20 per treatment) to reduce random variability. Skin burst pressure was measured on ten skin samples per treatment after incubation at the appropriate humidity and a temperature of about 20°C. The thickness and fresh weight of these samples were measured after burst testing. The remaining, intact skins were used for estimation of fresh weight and thickness on immediate removal from the humidification chamber.

2.5.3. Experiment 3

Disks were cut from the dry, outer skins of mature bulbs of two cultivars, cvs Hysam and Crossbow, cured and stored at 5°C after lifting from field experiments in late August 1997 until the date of the experiment (16 March 1998). The disks were incubated for 4 days in desiccators at high and low relative humidities, as for Experiment 2, except that filter paper was not used. Twenty disks per cultivar per treatment were removed when required and burst pressure tested. At this time, samples of 20 disks were also transferred from high to low humidity. These were incubated with control disks, which had been at low humidity throughout, for a further 2 days and then tested for strength in the burst unit. All samples were also used for estimation of strength, thickness and moisture content. The refinement of taking parallel samples for these different measurements, as done in Experiment 1, was found to be unnecessary.

2.5.4. Experiment 4

This examined the effect of a range of humidities between 0 and 100% RH on burst pressure of cvs Hysam and Crossbow from the same source as Experiment 3. Desiccators containing the following agents were equilibrated to the measured
Fig. 2. (A) Changes in weight of onion skin after successive transfers between a humid chamber and air. (B) Time course of weight increase of silica gel-dried skin during re-humidification in ambient atmosphere (Experiment 1).

Relative humidities indicated: silica gel, 17% RH; saturated MgCl₂·6H₂O, 38% RH; saturated Ca(NO₃)₂·4H₂O, 55% RH; saturated NaCl, 73% RH; water, 95% RH. Disks were cut, as in previous experiments, from dry outer skins and placed in these desiccators to equilibrate for 5 days after which they were burst-pressure tested. Some disks were also placed on filter paper in direct contact with water (WET treatment). These disks were tested for strength after only 2 days incubation in case the onset of microbial activity weakened the tissue. Temperature during incubation was about 24°C.

2.5.5. Experiment 5

Changes in stiffness, uni-directional stress and strain of skins from 20 bulbs of cv. Hysam from the same source as Experiment 3, were examined. Paired samples from the same mature dry outer skin of each bulb were incubated for 5 days at low (≈ 20% RH) and high (≈ 90% RH) humidities and a temperature of 23°C. To speed up stiffness testing, samples were cut and mounted on one end of the supporting card only (see above for method), prior to incubation. Samples were initially fixed at one end only of the card to prevent buckling or stretching caused by humidity-induced swelling or contraction. The free end of the sample was fixed to the card after incubation. This test takes several minutes, so an appropriate humidity was maintained around the sample by enclosing the test rig and circulating dry or humid air.

In all experiments, the atmospheres within desiccators were unstirred. Measurements of humidity were made by enclosing a capacitance-based sensor in each desiccator and noting the stable RH after the chamber had equilibrated. The sensor had previously been calibrated against a known standard in a controlled humidity chamber.

Significance of effects was determined by analyses of variance or regression using the Genstat statistical package (Genstat 5 Committee, 1993). All statistical errors were derived from these analyses and are quoted as least significant differences at $P = 0.05$ or confidence limits at $P = 0.95$.

3. Results

Changes in weight of a dry outer skin illustrate uptake and loss of moisture (Fig. 2A) after enclosure in and removal from a closed humid chamber (Experiment 1). From re-humidification of a skin dried over silica gel (Fig. 2B), equilibration is achieved in about 7 h with a $t_{1/2}$ of ≈ 1 h. These changes in weight illustrate the time required for the exchange of water vapour between skin and air to take place.

Multi-dimensional resistance to breaking of onion skins (Experiment 2), incubated in a closed chamber at 16% RH, was considerably less than for those incubated at > 95% RH (Table 1). In this experiment, skins at RH actually became wet as a result of contact with moist filter paper. This
increased their thickness considerably. The relationship between the burst pressure at skin breakage and skin thickness after drying (i.e. structural material) was different for the two treatments (Fig. 3A). Regression analysis showed that data for both humidity treatments shared a common slope ($14.8 \pm 9.14$ MPa mm$^{-1}$), but for skins incubated at higher RH the intercept was significantly higher ($F = 19.5$, $P < 0.001$) than that for skins incubated at lower humidity. When skin thickness after treatment (i.e. including moisture) was used as the independent variable (not shown), there was no significant effect of humidity on slope or intercept, a simple linear regression accommodating all of the data (intercept $0.27 \pm 0.40$, slope $10.7 \pm 4.14$ MPa mm$^{-1}$). The additional parameters of a quadratic model were not significant. In spite of the mechanistic logic of expecting zero burst pressure at zero thickness, regressions were not forced through the origin. It was deemed inappropriate because the absence of data as thickness approached zero did not permit the nature of the relationship between the variables to be defined.

In Experiment 3, skins from two cultivars that were known to differ in skin thickness and resistance to breaking illustrated a similar effect of incubation at different humidities on burst pressure to that observed in Experiment 2 (Table 2). Drying skins in a low humidity environment (16% RH) after incubation at high humidity (>95% RH) essentially reversed the effects (Table 2). In this experiment skins did not become wet and differences in thickness were not observed. Humidity again did not significantly affect the slope of the relationship between burst pressure and thickness (Fig. 3B); a common slope of $17.4 \pm$
Table 2
Responses of skins of two onion cultivars to incubation in environments differing in their relative humidities (Experiment 3)

<table>
<thead>
<tr>
<th>Incubation at:</th>
<th>Cultivar</th>
<th>Thickness after incubation (mm)</th>
<th>Moisture content (g g⁻¹)</th>
<th>Burst pressure (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16% RH</td>
<td>Hysam</td>
<td>0.048</td>
<td>0.028</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Crossbow</td>
<td>0.033</td>
<td>0.021</td>
<td>0.3</td>
</tr>
<tr>
<td>&gt;95% RH</td>
<td>Hysam</td>
<td>0.054</td>
<td>0.336</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Crossbow</td>
<td>0.033</td>
<td>0.333</td>
<td>1.2</td>
</tr>
<tr>
<td>16/16%</td>
<td>Hysam</td>
<td>0.051</td>
<td>0.049</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Crossbow</td>
<td>0.040</td>
<td>0.051</td>
<td>0.6</td>
</tr>
<tr>
<td>&gt;95/16%</td>
<td>Hysam</td>
<td>0.045</td>
<td>0.068</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Crossbow</td>
<td>0.037</td>
<td>0.061</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\[ \text{LSD (P = 0.05)} \quad 0.0090 \quad 0.0139 \quad 0.25 \]

<table>
<thead>
<tr>
<th>Significant factors in analysis of variance</th>
<th>Cultivar</th>
<th>Humidity</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P &lt; 0.001, \quad \text{LSD} 0.0045 ]</td>
<td>[ P &lt; 0.001, \quad \text{LSD} 0.0099 ]</td>
<td>[ P &lt; 0.001, \quad \text{LSD} 0.18 ]</td>
<td>[ \text{LSD} 0.013 ]</td>
</tr>
</tbody>
</table>

3.76 MPa mm⁻¹ being sufficient to describe the data. Humidity treatment was thus described in this experiment as well, by an increased intercept \((F = 181, \ P < 0.001)\). There was no significant effect of cultivar on this relationship and quadratic parameters did not improve the fit. The use of disk dry weight instead of thickness to represent structural matter did not alter the outcome of regression analyses of data in any experiment.

In Experiment 4, skins from cvs Hysam and Crossbow were incubated in closed chambers held at a range of relative humidities. Varietal effects on the measured variables were not observed, so the data from each were pooled. Moisture content of the skins increased with increase in RH (Fig. 4). Skin thickness was greatest at 95% RH and for skins allowed to become wet. Thicknesses of skins at relative humidities ranging from 17 to 75% were not significantly different. Multi-directional strength was greatest in skins from chambers held at 75 and 95% RH. Wetted skins, in this experiment, were weaker than skins incubated at the higher RH, but which were not in contact with liquid water. The outcome of regression analysis of burst pressure and skin thickness for this experiment (not illustrated) was similar to that for Experiments 2 and 3 with intercept increasing with humidity.

Stiffness of onion skins after incubation at 20 or 90% RH (Experiment 5) was much greater in drier skins, meaning that dry skins do not stretch readily under the same load per cross-sectional area as moist skins (Table 3). Adjusting estimates of stiffness by using skin thickness after drying the skins rather than skin thickness after humidity treatment did not alter the magnitude of this effect. Humidification therefore increased the flexibility of skins, enabling them to be stretched further before fracture (greater strain at failure in Table 3). In contrast to two-dimensional measurements of skin resistance to breaking by burst testing, this uni-directional tensile measurement demonstrated no significant difference between thickness-adjusted strengths of skins from the high and low humidities (adjusted stress at failure in Table 3). Estimates of failure stress not adjusted for skin thickness due to treatment show increased strength for skins incubated at low humidity compared with those at high humidity. Our measurements of failure stress for onion skins are of a similar magnitude to those of Smart, quoted by Brice (1994).
4. Discussion

It is well known that biological materials such as wood and paper are affected by water vapour and that their moisture content equilibrates with the humidity of the surrounding atmosphere (Lu and Leicester, 1997; Chalmers, 1998). Onion skins are composed principally of dead cell wall material (Ng et al., 1998) and thus might be expected to behave similarly. Our experiments demonstrate that changes in moisture content of onion skins occur within a relatively short time (h) and result in changes to their mechanical properties. These changes alter the ability of skins to stretch and the loading they can withstand before breaking.

Additional water may increase the flexibility of skins by reducing friction between adjacent cellulose microfibrils. It is however unlikely to increase strength in this way. Skins will simply extend further before breaking at the same load, as they did in our uni-directional tests (Table 3). It is possible that additional water within the structure provides more mechanical support for collapsed cell walls under stress by replacing air from spaces in the structure. This might provide an explanation for the increased resistance to breaking observed in our multi-directional tests. An alternative explanation for the effect of humidity may lie in the viscoelastic nature of biological materials. Onion skins stretch more readily when moist than when dry. If moist skins store energy more readily than dry skins as they are deformed, then they will break at greater loads. It is possible that the rate of pressure rise in the burst test exploits this feature and in essence reflects the difference in strain properties which humidification confers on skins.

Viscoelasticity might also provide a basis for the contrasting effects of humidity on resistance to breaking obtained in uni-directional and multi-directional tests. Uni-directional failure stress at breakage adjusted for skin thickness after drying (Table 3) was not significantly different for high and low relative humidities. However, burst testing suggested greater resistance to breaking after incubation at high RH. This difference might also be explained by the 'Poisson effect' (Vincent, 1992) in which material stretched in one dimension deforms in the other unrestrained dimensions (i.e. become narrower and thinner). If dry skins and moist skins behave differently in this respect then changes in aspect ratio may allow them to withstand similar loads in uni-directional tests. When clamped from all sides, as in the burst unit, displacement occurs in all directions with the possibility of compensating deformation in thickness only.

![Graph showing effect of humidity on onion skins](image)

*Fig. 4. Effect of incubation of onion skins in a range of relative humidities on thickness, moisture content and burst pressure (Experiment 4). Error bars illustrate least significant differences at P = 0.05.*
The relationships between burst pressure and skin thickness after drying suggest that the presence of moisture has raised the overall level of multi-directional resistance to breaking without altering the way that it changes with thickness (common slope, different intercepts). In Experiment 2, skin thickness was markedly increased when measured immediately after humidification. The relationship between skin burst pressure and skin thickness at this time suggested that humidification increased resistance to breaking by increasing cross-sectional area. Such swelling was not observed in Experiment 3 and only to a small degree in Experiment 4, but changes in resistance to breaking still occurred. Thus, it seems that hydrostatic swelling of skins caused by moisture uptake is not likely to be a mechanism for increasing strength. The nature of the relationship between burst pressure and skin thickness is relevant to the application of humidification to commercial bulbs, because skin thickness for bulbs from different varieties and environmental backgrounds may extend outside the range examined here. This may entail humidification protocols matched to particular batches of bulbs to accommodate a wider range of material.

In commercial situations, skins are subjected to mechanical forces from (i) changes in shape of bulbs as a result of drying out during storage; (ii) pressure from weight of bulbs in bulk storage; (iii) regrowth (dormancy breakage) after lengthy storage, and (iv) handling during harvesting and packing operations. Compliant skins are likely to withstand flexing and impact better than stiff skins. Similarly, stronger skins are likely to survive the rigours of commercial handling better than weaker skins. Humidification permits conditioning of the skins and is reversible. While RH is recognised as an important variable during curing and storage of commercial onions, it is not controlled during post-storage operations and is not used deliberately to modify skin condition. These results suggest that there is potential to develop post-storage protocols based on temporary short-term increases in humidity and that these will result in improved bulb quality by reducing subsequent skin damage and loss.

Acknowledgements

The Ministry of Agriculture Fisheries and Food, UK funded this work. We are grateful to Dr James Lynn for statistical advice and to Dr H.R. Rowse, Dr L.R Benjamin and Mr N.R. Parsons for helpful comments on the manuscript.

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