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SOME PROPERTIES OF MUSHROOMS

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A b s t r a c t. The results of some tests to detach mushrooms from their mycelium by the application of torque are presented. Upper thresholds for torque and angle of twist in detaching mushrooms may be defined. A series of compression tests on segments of white mushroom cap tissue was also carried out. Tissue was found to be significantly stiffer when measured perpendicular to the stem axis, than parallel to it. A positive correlation was found between stiffness and density, the latter varying markedly from cap to cap. No obvious correlation was found between stiffness and moisture content.

K e y w o r d s: mushrooms, stiffness, density detachment from the bed

INTRODUCTION

The use of automatic and robotic techniques to harvest vegetable produce is receiving increased attention with the introduction of improved methods of image analysis, sensing and handling. With a view to developing robotic systems suited to the specific requirements of horticulture, in which non-uniformly shaped items, susceptible to damage by exposure to excessive local forces, need to be handled at maximum speed, work has been under way at Silsoe Research Institute to design a system for harvesting cultivated mushrooms, *Agaricus bisporus* [2-4]. This particular crop is a challenging target to the equipment-designer, combining a very random shape and distribution over the growing-medium, together with a high susceptibility to mechanical damage. At an early stage, it was decided to base the harvesting system on rubber suction cups, capable of gripping onto the tops of the mushroom caps by means of an applied vacuum. Whilst the characteristics of the rubber suction cups were well-defined, relatively little was known about the mechanical behaviour of mushrooms, both in their detachment from the growing-medium, as well as in the response of mushroom flesh to applied loads.

This paper describes initial tests to characterise the detachment of mushroom fruiting-bodies from the bed. The results of some mechanical tests on mushroom cap tissue are also presented.

MUSHROOM DETACHMENT

Procedure

Manual picking of mushrooms usually involves a visual assessment of mushroom distribution on the bed, identification of mushrooms in the desired size-range, location of mushrooms with adjacent space, application of lateral force to the cap in the direction of the space, with resultant bending and ultimate fracture of the stem callus close to the bed. Stem fracture having been achieved, any remaining connection to the bed is broken by means of a twisting action applied to the cap, prior to lifting the mushroom away from the bed. This sequence ensures that a minimal amount of mycelium is pulled up with the mushroom each time, and the process is repeated until the desired number of mushrooms has been picked. Automated picking need not necessarily imitate manual picking, and several methods were considered.

Assuming the mushroom cap to be gripped, force may be applied in several directions, as shown in Fig. 1, either vertically (a), horizontally (b), or about horizontal or vertical rotational axes (c) or (d). Methods (b) and (c) both require space around the mushroom, necessitating sophisticated image analysis prior to picking, while methods (a) and (d) can be applied to densely-packed mushrooms. A vertical pull directly upwards as in (a) tends to uproot large amounts of mycelium with the mushroom. It was thus decided to investigate method (d) as offering the simplest solution.

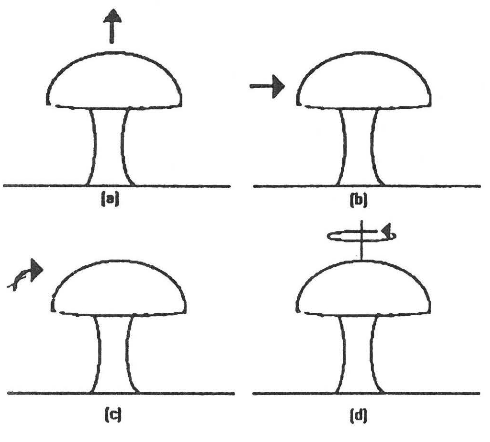

Fig. 1. Possible modes of mushroom detachment.

Pre-spawned mushroom compost, in the form of bags, and latterly blocks, was obtained from a local mushroom farm at the 'pinning' stage, and grown on under conditions of controlled temperature, humidity and carbon dioxide concentration, commensurate with the formation of several successive crops or 'flushes' of mushroom fruiting bodies. Periodically, bags or blocks were removed from the growing chamber and situated beneath an experimental picking-head, designed to suck onto the mushroom cap and rotate it until the mushroom was detached from the bed, whilst simultaneously monitoring the torque and the angle of rotation (Fig. 2). Mushrooms were picked at the closed-cap stage of development. Care was taken to avoid any application of upward force to the caps during suction-cup attachment by the expedient of mounting the suction-cup on a vertically-free (weak)-spring-supported shaft. Torque was applied by means of a toothed belt rotating a toothed pulley, movement of the belt being effected via an interlocking yoke connected to a linear force-transducer, itself mounted on a motor-driven table, capable of linear motion. Operation of the system involved the application of suction to the rubber cup, lowering of the system until the cup attached itself to the mushroom cap, and activation of the motor-driven table, moving the force-transducer, yoke and belt, which moved the toothed pulley to rotate the rubber cup. The rubber cup was rotated at a rate of 20 deg/s in all tests. Results were recorded on a Hewlett-Packard x-y plotter. Figure 3 shows a typical trace for the detachment of a mushroom, together with a trace showing the torque/angle characteristic of a typical rubber suction cup. After the detachment of each mushroom, measurements were made of mean cap diameter, mean stem top diameter, mean stem base diameter, overall height and height of the cap. Cases in which other factors contributed to the recorded torque, e.g., the interference of adjacent mushrooms, or mushrooms at acute angles to the bed, were individually noted and subsequently disregarded in the analysis of results presented below.

It was noted that the mushroom caps appeared to be very well-attached to the stems, to the extent that the applied torques only rarely separated cap from stem. A very small sample of mushrooms was subjected to the deliberate torque of the cap from the gripped stem in order to indicate the degree of the 'safety factor' inherent in the picking method.

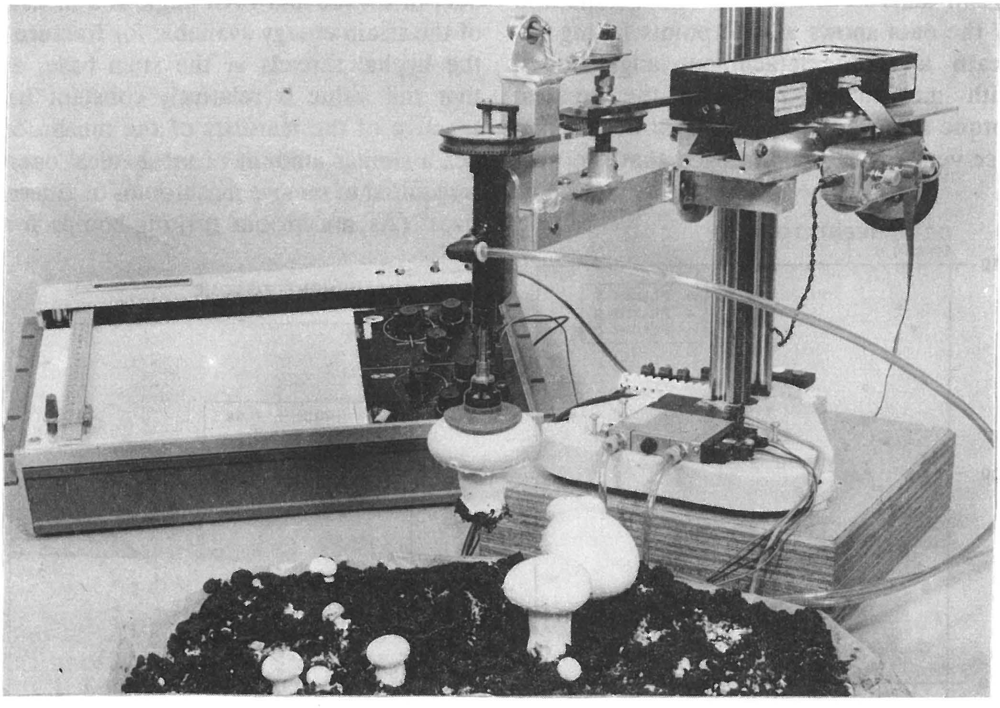

Fig. 2. Photograph showing torque/angle measuring equipment.

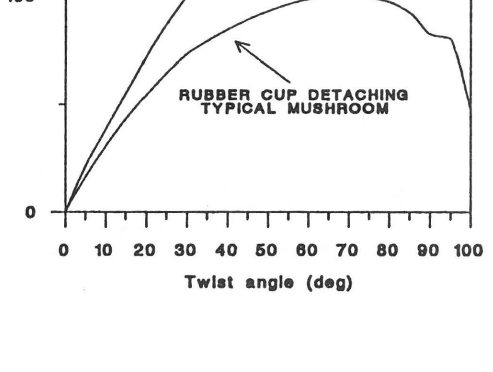

Fig. 3. Rubber cup characteristic and a typical torque/angle trace for mushroom detachment.

Results

In every case, the torque rose to a maximum coincident with the point of detachment. Figure 4 summarises detachment torque and angle of detachment data for flush 1, flush 2 and flush 3 mushrooms. Figures 5 and 6 show detachment torque plotted against stem base area and cap diameter, respectively. Figure 7 shows a comparison of stem/bed detachment torque with cap/stem detachment torque for a sample of ten mushrooms.

Discussion

From Fig. 4, it can be seen that the bulk of the mushrooms were removed at low torque and at low twist angles. From the viewpoint of the harvesting mechanism, it is clear that an available torque of 200 Nmm, combined with a rotational capacity of 180 degrees (allowing for suction-cup twist), should facilitate removal of the vast majority of mushrooms from the bed. An examination of the data shows all the points falling beneath a torque/detachment angle locus, with mushrooms requiring the greatest torque removed at the smallest angles, and vice-versa. It is hypothesized that the product of torque and twist angle is a measure of the strain energy available for fracture of the hyphal threads at the stem base, and that this value is relatively constant irrespective of the maturity of the mushroom, i.e., a similar amount of mechanical energy is required to remove mushrooms of different sizes. (As mushroom fruiting-bodies form

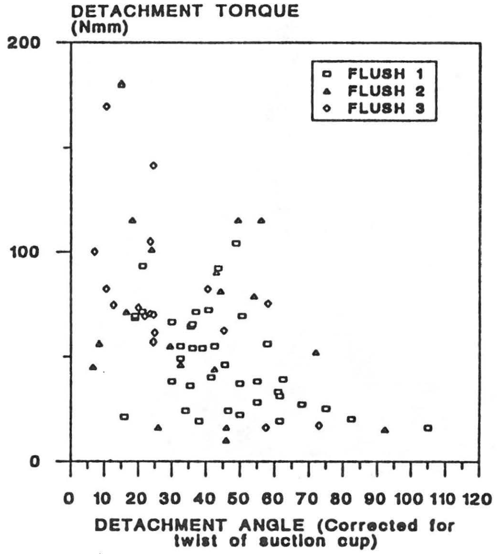

Fig. 4. Stem/bed detachment torque vs. detachment angle.

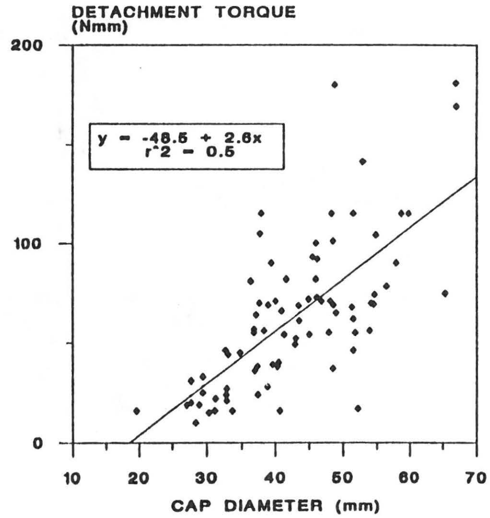

Fig. 6. Stem/bed detachment torque vs. cap diameter.

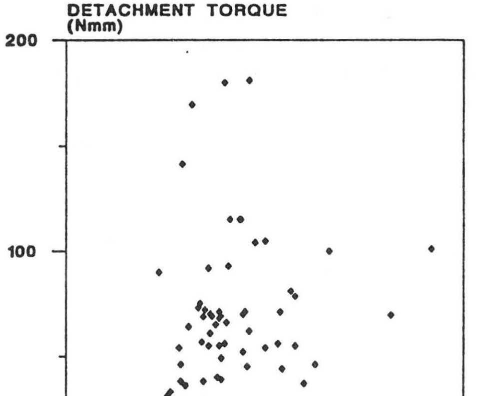

Fig. 5. Stem/bed detachment torque vs. area of stem at base.

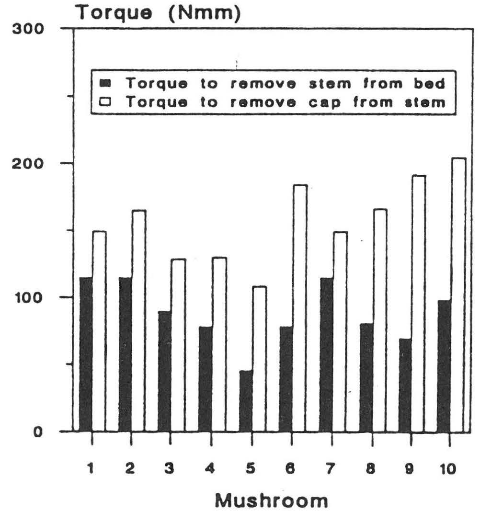

Fig. 7. Comparison of torques to pick mushrooms from bed, with torques to remove cap from stem.

so rapidly, it is conceivable that the amount of dry matter available within the fruiting-body does not change significantly. This could provide an explanation for the above behaviour).

A consideration of Fig. 5 suggests that there is no clear relationship between the area of the base of the stem, and the torque required for its removal from the mycelium. This may seem surprising, although a close examination of the fracture sites shows that the stem is typically attached to the mycelium at several small points, and that it is the area of these attachments which is of relevance, rather than the stem area per se.

Although cap diameter may be difficult to relate to detachment torque, it is a parameter easily available to image analysis and hence might be useful. Figure 6 indicates a definite trend towards a linear relationship between these two parameters. It is thought unlikely that cap diameter can influence detachment torque, other than as a general reflection of mushroom size.

Figure 7 suggests that the removal of mushrooms by means of twisting of the cap is unlikely to result in cap detachment from the top of the stem. This is important insofar as such losses would be unacceptable in a harvesting machine.

MECHANICAL TESTS ON MUSHROOM TISSUE

Procedure

Tissue samples cut from a small number of mushrooms were subjected to mechanical testing in order to gain some understanding of mushroom behaviour in response to applied loads.

Large closed-cap first-flush mushrooms were picked manually and transferred to sealed plastic bags. Cylindrical cores, nominally 9.4 mm diameter, were trepanned from each mushroom cap using a rotating cork-borer, entering the cap either longitudinally and centrally (parallel to the stem axis), or laterally, as close to the top of the cap as possible. (The intention was to test the properties of dense, white, cap hyphal tissue, hence any samples including gill tissue were discarded). Cylinders were cut to a nominal length of 5.3 mm using a razor-blade and mitre-block, and wrapped in cling-film until tested.

Sample dimensions were measured using a shadowgraph with 10x magnification, to a resolution of 0.1 mm. Each sample was weighed using a Mettler balance capable of resolving 0.1 mg. A sample from each cap tested was also analysed for moisture content. Compression tests were carried out on a Davenport-Nene loading frame, using a 260 N capacity load-cell. The lower platen was fixed in a horizontal plane, the upper platen being self-aligning by means of a ball-joint. Samples were loaded at 2 mm/min over a distance of 2.5 mm in each case. Data was recorded digitally for subsequent analysis by means of an analogue-to-digital converter and associated software. Tissue samples from 28 mushrooms were tested, 14 in the longitudinal axis, 14 in the transverse axis.

Results and discussion

Figure 8 shows a typical stress-strain curve with the addition of a low-strain tangent modulus (line of maximum slope after any initial 'take-up' of slack due to sample/platen misalignment etc.). The shape of the stress-strain curve was representative of both transverse and longitudinal orientations, an initial gradual diminution of stiffness with increasing strain being succeeded by increasing stiffness. Such a shape may be explained by the three-dimensional net-like structure of hyphal cells, separated by air-spaces, progressive compression collapsing interconnected voids until cell-cell contact occurs, with concomitant increase of stiffness.

Low-strain tangent moduli were tabulated for all the samples, together with density (calculated from weight and dimensions) and moisture contents, as shown in Table 1. The mean stiffness in the longitudinal orientation was found to be 0.524 MPa, with a standard deviation of 0.135, while mean

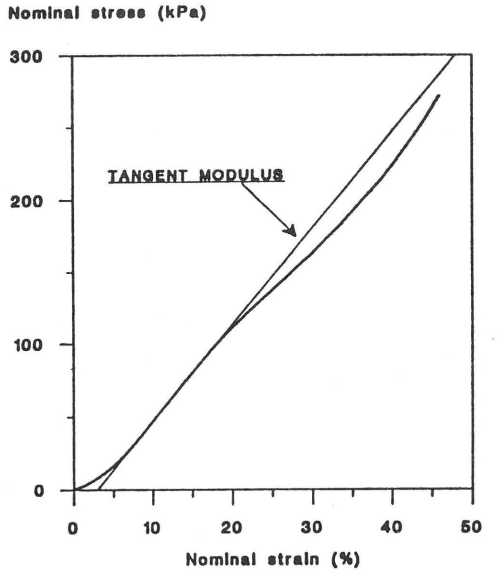

Fig. 8. A typical stress-strain curve for white mushroom cap tissue, showing tangent modulus.

stiffness in the transverse orientation was 0.710 MPa, with a standard deviation of 0.141. Using a two-sample T-test, the difference in mean stiffness was found to be significant at the 0.1 % level.

Previous workers have measured firmness of whole mushroom caps [1], but their results, expressed in kg/mm, cannot easily be compared with the compressive modulus of mushroom cap tissue, expressed in MPa.

Figure 9 shows low strain compressive modulus plotted against tissue density for longitudinal and transverse orientations, respectively. Despite the scatter of results, there appears to be a clear correlation between stiffness and tissue density. It is also worth noting that the density of mushroom cap tissue varied widely from mushroom to mushroom, in the range 0.5 to 0.8 g cm^{-3}.

Low strain compressive modulus did not appear to correlate with moisture content, as shown in Fig. 10, although the variation in moisture content between samples was comparatively small. Knowing that the hyphae consist predominantly of water, it is possible to infer that the volume fraction of void space in the white cap tissue varied between 25 and 50 %.

Table 1. Results of cap tissue tests

Sample No.	Low-strain modulus (MPa)	Density (g cm^{-3})	Mositure content (% wet basis)
	Longitudinal		
1	0.492	0.74	93.8
2	0.479	0.67	94.1
3	0.380	0.55	91.6
4	0.316	0.52	93.4
5	0.678	0.63	93.8
6	0.513	0.71	93.9
7	0.843	0.82	92.9
8	0.539	0.78	93.7
9	0.492	0.66	93.2
10	0.672	0.76	93.1
11	0.551	0.75	93.6
12	0.515	0.59	91.7
13	0.475	0.52	91.3
14	0.385	0.55	92.4
	Transverse		
1	0.695	0.73	94.1
2	0.865	0.74	93.7
3	0.619	0.64	92.9
4	0.868	0.78	92.7
5	0.663	0.63	93.8
6	0.835	0.76	93.5
7	0.952	0.71	92.8
8	0.615	0.67	92.4
9	0.625	0.70	93.9
10	0.817	0.75	93.5
11	0.433	0.60	93.2
12	0.720	0.70	93.2
13	0.579	0.70	93.1
14	0.656	0.61	91.1

CONCLUSIONS

Tests were carried out to determine torques and angles of rotation necessary to remove mushroom fruiting-bodies from their growing medium. Due to the considerable spread of results, it was found that torques up to 200 Nmm, with rotations up to 180° would be necessary to remove all mushrooms from the bed. Little relationship was found between stem base diameter and detachment torque. (A better means of assessing real areas of fracture might have yielded a better correlation). Cap diameter appeared to exhibit a linear relationship to

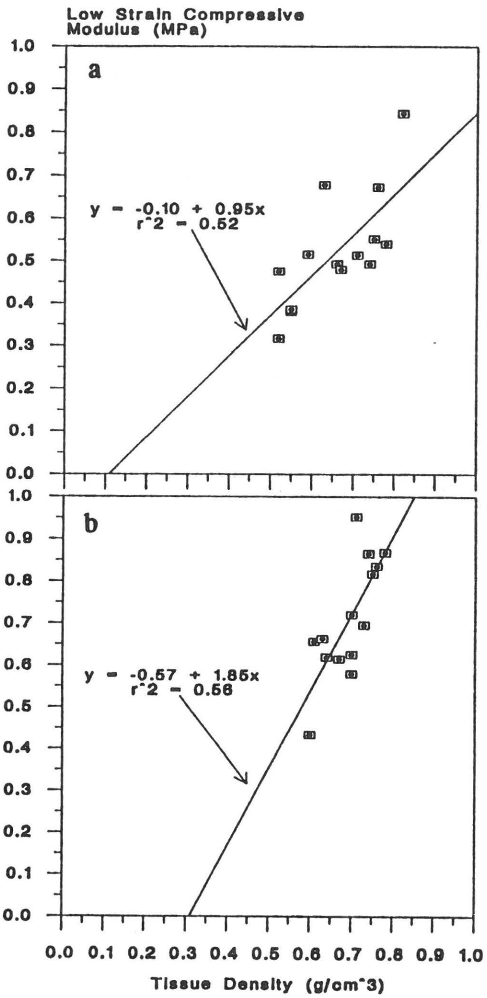

Fig. 9. Low strain compressive modulus in the longitudinal axis (a) and in the transverse direction (b) vs. density for white mushroom cap tissue.

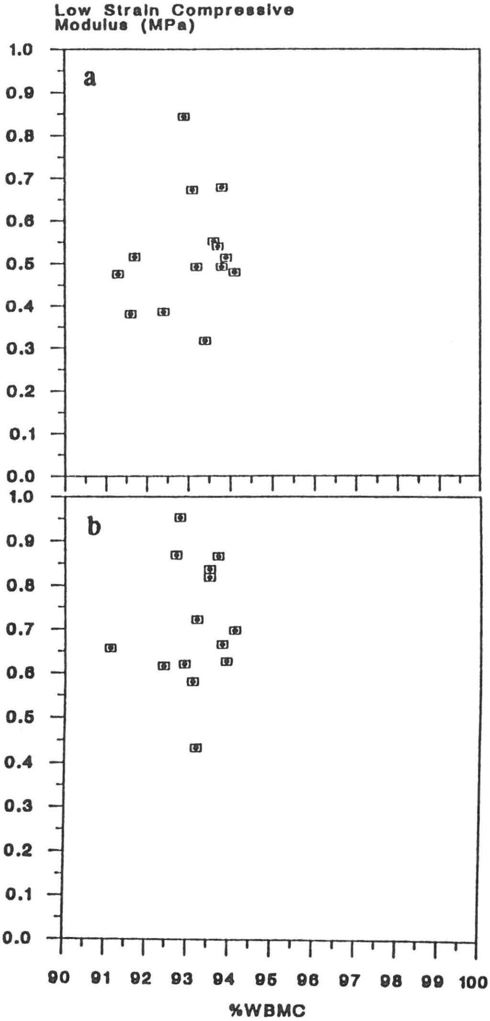

Fig. 10. Low strain compressive modulus in the longitudinal axis (a) and in the transverse direction (b) vs. moisture content.

detachment torque for as yet unexplained reasons. Limited tests suggested that detachment of cap from stem was unlikely to occur prior to detachment of stem from bed. It is suggested that further work examine the structure of the detachment zone in greater detail, with a view to understanding the failure mechanism.

As a first step towards the mechanical characterisation of mushroom fruiting-bodies, quasistatic compression tests were carried out on samples of white cap tissue. Generally, tissue was found to be stiffer in the transverse direction, compared to the longitudinal direction, and stiffness appeared to correlate with tissue density, but not with tissue moisture content. Further work should relate these properties to structure, and should also consider tissue failure mechanisms.

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