

Mechanical Behavior of Oats: The Groat Effect

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ABSTRACT

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To evaluate the mechanical behavior of groats with constant mass and moisture content, individual groats were compressed along the major axis between parallel flat plates. Compression versus tension testing was adapted easily to groats, which are weaker along the major axis. Regression of maximum apparent stress on moisture content suggested that the proportionality constant was a function of an undefined biological difference (UBD) among tested samples and the y-intercept depended on groat mass and UBD. No brittle-ductile transition in the range of 9–30% mois-

ture was observed regardless of genotype. Groats in general tended to fail by plastic compression at low moisture content (9–10%). Groats at high moisture content (>12%) generally buckled and burst near the midpoint of the crease, suggesting higher stress around the crease regardless of genotype. Apparent maximum stress should be considered as an average for a genotype. Knowledge of specific groat characteristics (including but likely not limited to mass and moisture) and how they influence apparent mechanical behavior should lead to improvements in oat milling.

With the exception of kilning, major unit operations in oat milling (and grain processing in general) are mechanical systems. Predictably, numerous studies on the mechanical behavior of grain have been done; however, most involve a single genotype (Zoerb and Hall 1960) and few involve oats. The most common materials science testing method for grain is compression versus tension testing because of grain size and shape limitations (Morrow and Mohsenin 1966). The fracture mode of a material depends on the mechanical test, strain rate, plasticizer content, and other factors; fracture can be brittle or ductile depending on the situation. Callister (1994) characterizes brittle fracture by rapid crack propagation without appreciable deformation. Ductile fracture occurs with considerable plastic deformation involving high-energy absorption before fracture (Callister 1994). Prochazka et al (1979) subjected oats with moisture contents of 9–35% to uniaxial compression along the major and minor axes. Oats are weaker along the major axis versus the minor axis (Bilanski 1966), proximal end down versus ventral side down, respectively. Maximum apparent stress decreases as moisture content increases from 9 to 20 percent, and then remains more or less constant according to Prochazka et al (1979). The mechanical behavior of oats (and grains in general) is viewed as apparent behavior because these materials violate assumptions of homogeneity, isotropy, and continuity required in solving materials science problems (Morrow and Mohsenin 1966). In another study, several grains including oats were classified as elasto-brittle when dry and elasto-plastic when containing 17% moisture (Naumov et al 1978). These results (Naumov et al 1978; Prochazka et al 1979) suggest that a brittle-ductile transition, a change in the mode of fracture, exists in oats.

Many materials are brittle at low moisture content and ductile at high moisture content, but not all materials display a brittle-ductile transition. In many grains, maximum apparent stress is inversely proportional to moisture content, with no evidence of a plateau at high moistures (Bargale et al 1995), and fluctuates within a wide range (Naumov et al 1978; Al Saleh and Gallant 1985). Increasing moisture content causes plasticization of grain in general. This has been demonstrated in wheat, maize, rapeseed, rice, soybeans, barley, cowpeas, and oats (Zoerb and Hall 1960; Shpolayanskaya 1952; Goncharova 1962; Bilanski 1966; Shelef and Mohsenin 1969; Husain et al 1971; Davison et al 1975; Herum et al 1979; Al Saleh and Gallant 1985; Pappas et al 1988; Dobraszczyk 1994; Bargale and Irudayaraj 1995; Bargale et al 1995). High moisture grain is less resistant to uniaxial compression and more resistant to impact dam-

age (Shpolayanskaya 1952; Mohsenin 1986). Moisture enables grain to withstand more mechanical energy before impact damage occurs. As pointed out by Bilanski (1966) and Mohsenin (1986), a high-energy value does not necessarily imply that maximum apparent stress is high because energy depends on stress and strain.

Progress in oat breeding over the past 20 years warrants a reexamination of the mechanical behavior of more contemporary oat genotypes. Recent work (Doehler and McMullen 2000) has done this to some extent using a single kernel characterization system (SKCS); the investigators reported that the SKCS hardness index was correlated significantly with β -glucan content and average groat mass for a 10-g groat sample. Groat characteristics in addition to average mass and β -glucan content may influence mechanical behavior. We are not aware of any studies assessing the mechanical behavior of groats among genotypes while maintaining constant groat mass and moisture content. The specific objectives of this study are to develop a parallel flat plate compression test using a texture analyzer (TA.XT2i, Texture Technologies, New York) and to determine whether in addition to groat mass and moisture content, other biological characteristics affect the mechanical behavior of groats.

MATERIALS AND METHODS

Sample Preparation

Oats (*Avena sativa* L. 'Newman' and '0A899-2') were divided randomly by a riffle-style divider (model H-3985, Humboldt Testing Equipment, Norridge, IL) into 10-g samples that were dehulled manually and sorted by groat mass. Newman and 0A899-2 were selected because they were available; differences in mechanical behavior for specific genotypes were unknown. Samples were ground in a centrifugal Retsch mill (model ZM-1, Brinkman, Haan, Germany) through a 0.5-mm screen and dried according to Approved Method 44-15A (AACC 2000) for initial moisture content determination.

Groats were conditioned with distilled water in sealed glass vials to attain moisture contents ranging from the initial moisture content (9–10% wb) to the conditioned moisture content of 30% wb. Vial contents were mixed by gentle rolling for 15 min, refrigerated for one week, and equilibrated to ambient temperature for 1 hr before use. Final moisture content was calculated from the change in groat mass and the initial moisture content.

Groat maximum length (L_0) and width (W) were measured by digital image analysis using an IBAS Kontron Image Analysis System (v. 2.0, Kontron Electronic GmbH, Eching, Germany). Groats were placed ventral side down on a copy stand with sub-stage illumination. Images were captured with a Sony-89C CCD camera (model XC-77) with 512×480 pixels/frame (0.1887 mm \times 0.2400 mm resolution) and a Tamron lens (F-28 mm).

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Compression Tests

Given that the most common materials science testing method for grain is compression, individual groats were compressed along the major axis (positioned proximal end down) between parallel flat plates coated with sandpaper (210N, 3M) using a texture analyzer (TA.XT2i). Compression along the major axis was chosen because oats tend to be weaker along the major axis versus the minor axis. The test was based on descriptions and definitions given by Callister (1994). However, oat morphology required new details like plates coated with sandpaper. A schematic diagram of the test is shown in Fig. 1. The texture analyzer was programmed such that the upper plate traveled down $0.5 L_0$ mm relative to the initial position at a rate of 0.8 mm/sec, and then returned at the same rate to the initial position. The distal end of the groat defined the initial position. The lower plate was stationary. Load versus time curves were recorded. In an attempt to minimize morphological factors, load and time were normalized to the respective parameters of apparent stress and strain. Apparent stress (σ) was defined by the relationship $\sigma = F/A_0$, where F is the instantaneous load and A_0 is an approximation of the original groat cross-sectional area, $A_0 = \pi W^2/4$. Apparent strain (ϵ) was defined as

$$\epsilon = \frac{L_0 - L_i}{L_0} = \frac{\text{(rate of upper plate)} \times \text{time}}{L_0}$$

where L_i is the instantaneous length.

Statistical Analysis

Weighted linear regression, using the least squares algorithm, of apparent maximum stress on moisture content was calculated with Arc and the Xlisp-Stat system (v. 3.04, University of Minnesota, St. Paul, MN), which is described in detail by Cook and Weisberg (1999). Weights were defined as the number of replicated compression tests n . Figures were constructed with SigmaPlot (v. 5.0, SPSS, Inc., Richmond, CA).

RESULTS AND DISCUSSION

Observations

Groats tended to buckle and fail by crushing, or plastic compression, at low moisture content (9–10% wb). At high moisture content (>12% wb) groats generally buckled and burst near the midpoint of the crease, tore open along the crease, and then bent at the dorsal side. This was somewhat expected given the study concerning stress distribution in compressed wheat by Arnold and Roberts (1966). They identified areas of high stress around the extremity of the crease. There was likely a mechanical behavior difference between the central endosperm and the bran.

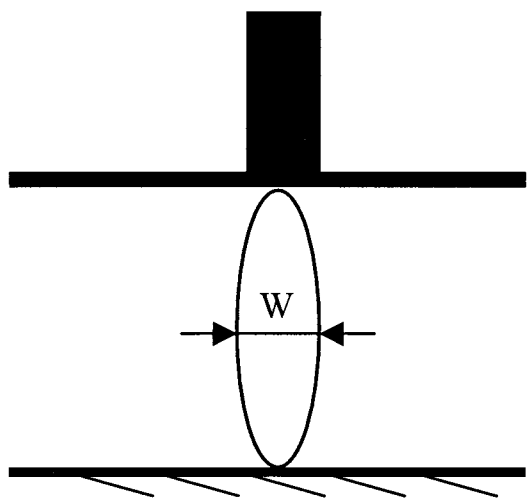


Fig. 1. Schematic diagram of the compression test.

Resistance to Compression

Representative variation in apparent stress as a function of apparent strain at 9, 20, and 28% wb moisture is shown in Fig. 2. Initially, all three curves were roughly linear. Departure from linearity represented a transition from elastic to plastic deformation. At a strain of ≈ 0.1 , apparent stress dropped as initial yielding and perhaps fracture occurred. The nonlinear increase in apparent stress (strain of 0.1–0.2) was likely due to crushing, followed by plastic yielding, further compression, and likely failure. The final plateau (strain of 0.4–0.5) in the higher moisture curves (20 and 28% wb) was likely due to bending at the dorsal side.

The decrease in resistance to compression upon increasing moisture content may have been due to a change in the friction coefficient, the average force required for a polymer segment to push through local surroundings at unit velocity (Ferry 1970). Shelef and Mohsenin (1969) offered a similar explanation regarding the compression behavior of conditioned maize. In general, the friction coefficient decreases as the free volume of a material increases (Ferry 1970). Al Saleh and Gallant (1985) showed that increasing wheat moisture content increased free volume, and decreased resistance to uniaxial compression. Free volume has also been considered as a factor affecting the initial shape of a stress-strain curve of wheat (Shelef and Mohsenin 1967).

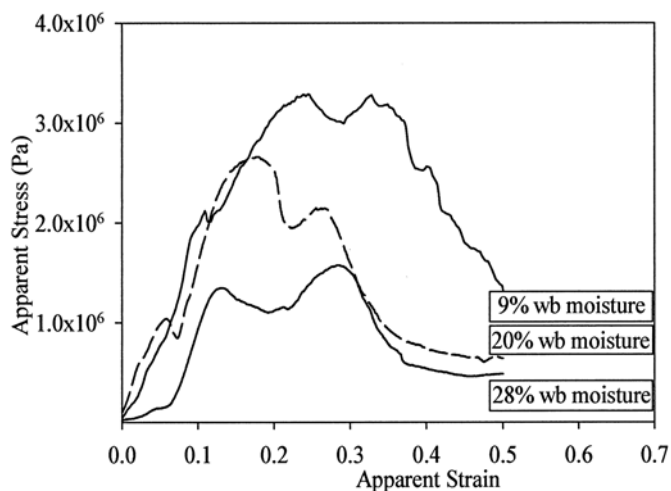


Fig. 2. Apparent stress as a function of apparent strain representative of cv. Newman, groat mass 0.039 ± 0.006 g, and the effect of groat moisture content.

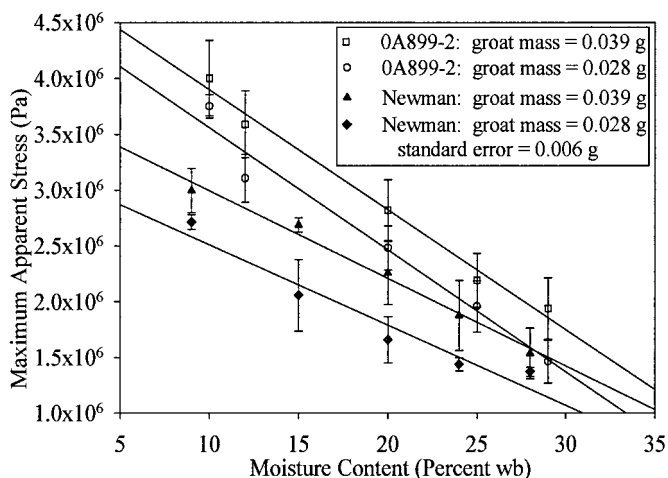


Fig. 3. Maximum apparent stress as a function of groat moisture content of cv. Newman and 0A899-2, and the effect of groat mass and biological variability. Data points are means ($n = 4-6$ compression tests) and error bars are standard errors.

Maximum Apparent Stress

For constant groat mass and moisture content, maximum apparent stress was affected by an undefined biological difference (UBD) among tested samples. This was not expected based on knowledge of the particular genotypes. Figure 3 shows maximum apparent stress as a function of groat moisture content. Despite variation in apparent maximum stress for each genotype at constant groat mass and moisture content, the data fit a linear model well ($R^2 = 0.94\text{--}0.99$). No obvious brittle-ductile transition was evident. Rather, maximum apparent stress was inversely proportional to moisture content. The proportionality constant (Fig. 3) appeared to be a function of UBD given similar observed slopes within a genotype and different slopes between genotypes. Differences between genotypes seemed greater at low moisture content. Confidence intervals (CI) for the slopes of Newman and 0A899-2 did not overlap while CI within a genotype overlapped ($\alpha = 0.1$). The y -intercept (Fig. 3) appeared to be a function of groat mass and UBD as the intercepts appeared different for each genotype and increased with increasing groat mass. CI for the 4 y -intercepts did not overlap ($\alpha = 0.12$). At $\alpha = 0.1$, the upper CI limit of Newman (groat mass 0.028) just overlapped the lower CI limit of Newman (groat mass 0.039). The number of moisture contents investigated (5) was small and therefore the number of degrees of freedom used in the quantile calculation was small, resulting in large CI.

CONCLUSIONS

Weighted linear regression of maximum apparent stress on moisture content suggested that for constant groat mass and moisture content, the mechanical behavior of groats depended on an undefined biological difference among tested samples. No obvious brittle-ductile transition in the range of 9–30% moisture was evident. Groats failed by crushing at low moisture content (9–10%). They tended to buckle and burst near the midpoint of the crease, tear open along the crease, and then bend at the dorsal side at high moisture content (>12%). Apparent maximum stress should be treated as an average for a genotype. Groat characteristics (including but likely not limited to mass and moisture) can be manipulated to influence such an average value. How (statistically) the conditional distribution of apparent mechanical behavior changes as specific groat characteristics change should validate the compression test presented here. Knowledge of the specific characteristics and how they influence apparent mechanical behavior should also lead to improvements in oat milling. This will be the subject of our next publication.

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