Oat Grain Density Measurement by Sand Displacement and Analysis of Physical Components of Test Weight

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ABSTRACT

Test weight or bulk density of oats (Avena sativa L.) has a major influence on the monetary value of oat grain. We hypothesize that test weight can be attributed to grain density and packing efficiency. We have measured oat grain volume and density by a sand-displacement method and derived the packing factor for six oat cultivars grown in three environments. Volumes of individual grains were 31-38 mm³ and were highly correlated with grain mass. Grain densities were 0.96-1.03 g/cm³. Packing efficiency, defined as the space proportion occupied by the grains, was 53-55%. Regression analysis suggested that 78% of the variation in intact grains was only 1.44 g/cm³. The difference was attributed to air pockets within the wheat grain. They then used paraffin to seal pores on the wheat grain and, after correcting for the mass and volume of the paraffin, determined the envelope density of the wheat grain to be 1.37 g/cm³. Thus, about half of the air pockets in the wheat grain were open to the outside. Martin et al. (1998) measured wheat grain density by displacement of manometer oil. They estimated wheat grain density to be 1.28 g/cm³ in healthy grains and lower in sprouted and diseased grains. These values are probably closer to envelope densities than those determined by gas pycnometry, Yamazaki and Brigg (1969), Troccoli and DiFonzo (1999), and Ghaderi et al. (1971) using gas pycnometry all concluded that the most variation observed in test weight in wheat was due to variation in packing efficiency, which varied from 53 to 57%.

The envelope volume of oat grains was relatively difficult to determine. The measurements of Zink (1935) using mercury displacement would appear to be envelope volume measurements. They estimated oat grain specific gravity to be 1.01, and packing efficiency to be 48.7%. More recently, Nelson (2002) using gas pycnometry estimated oat grain density to be 1.3 g/cm³. A comparison of these values gives some indication of possible porosity of the oat grain. However, modern laboratories would not consider mercury displacement to be a satisfactory method because of the toxicity of mercury. Thus, we have sought alternative approaches to use in the measurement of envelope volumes of oat grains.

In this study, we developed a silica sand-displacement method to measure envelope volumes of oat grains, groats, and hulls. Our objective was to estimate oat grain density and grain packing efficiency to determine the relative roles in determining test weight in oats. We also sought to test hypotheses concerning the relative roles of grain density, hull volumes, and hull density, and volumes of empty space within the oat hulls in determining grain density.

MATERIALS AND METHODS

Plant Material

Six oat (Avena sativa L.) cultivars (AC Assiniboia, CDC Dancer, HiFi, Morton, Wabasha, and Vista) were grown at three locations (Carrington, Edgeley, and Fargo) in North Dakota in 2004. A seeding rate of 86 kg/ha was used for all experiments. Herbicide treatments consisted of a preemergence application of 3.93 kg of propachlor/ha and postemergence application at the three-leaf stage with a tank mix of 0.14 kg of thifensulfuron/ha, 0.07 kg of tribenuron/ha, and 0.14 kg of clopyralid/ha.
Experimental units consisted of four rows 0.3 m apart and 2.4 m long. The two center rows were harvested with a two-row binder and threshed with a plot thresher. Grain was cleaned using an air screen cleaner to remove chaff.

Sand Displacement

Routinely, oat grain and groat samples of 25 g were used for volume analysis by sand displacement, although samples as small as 5 g could be analyzed. Fine white silica sand was used for oat grain volume measurements. Sand that was purchased from a hardware store designed for sandblasting and sand collected from a beach (Siesta Beach, Sarasota FL) both proved satisfactory for the procedure. Sand was poured into a steel measuring cup a with level top designed for cooking. Cups with volumes of 59, 78.5, and 118 mL were used with identical results. The cup size used varied according to the bulk volume of sample being analyzed, where the volume of the sample usually did not exceed one third of the volume of the measuring cup. A 78.5-mL cup was used for a 25-g sample of oat grain.

The cup was filled to overflowing with sand and then while grasped by the handle, was tapped lightly against the bench for about 20 sec to uniformly pack the sand. This packing procedure was necessary to obtain reproducible results. A straight edge was then used to level the sand in the cup. The sand in the cup was then emptied into a holding container, and the oat sample was introduced into the cup. Sand in the holding container was then introduced back into the measuring cup containing the oats until the cup was about half-filled. The oats and the sand were then mixed thoroughly with a metal spatula to obtain complete contact of the sand with the oat grains and to eliminate air pockets. The remaining sand in the holding container was then introduced back into the cup with the oats. The cup containing the sand/oat mixture was then tapped again for 20 sec to obtain uniform packing and excess sand was then leveled off from the cup with a straight edge. The mass of the sand displaced in the cup by the oats was then measured. Grains were separated from the sand by hand-sieving on 600-μM mesh sieves (U.S. standard testing sieves, #35 mesh, A.T.M., Milwaukee, WI). This procedure was repeated four times for each sample and the mean displaced sand mass was used for calculations.

The volume of the oats in the sample was obtained by dividing the mass of the displaced sand by the measured bulk density of the sand (1.65 g/cm³).

\[
\text{Oat sample volume (cm}^3) = \frac{\text{Displaced sand mass (g)}}{\text{Sand bulk density (g/cm}^3)}
\] (1)

The mean oat grain volume was obtained by dividing the volume of the oat sample by the number of grains in the sample.

\[
\text{Mean oat grain volume (cm}^3/\text{grain}) = \frac{\text{Oat sample volume (cm}^3)}{\text{Number of grains (n)}}
\] (2)

The number of grains in the sample was obtained by physically counting the grains by hand. Mean grain mass was obtained by dividing the sample mass by the number of grains in that sample. For ease of expression, the mean grain volumes are expressed as mm³/grain. Mean grain mass is expressed as mg/grain, also for ease of expression. Mean grain density was obtained by dividing the mean grain mass by the mean grain volume.

\[
\text{Oat grain density (g/cm}^3) = \frac{\text{Mean grain mass (g)}}{\text{Mean oat grain volume (cm}^3)}
\] (3)

Packing efficiency was defined as the proportion of the packing container occupied by grains. We estimated this from the ratio of the test weight (or bulk density) and the grain density, multiplied by 100. It is necessary that the test weight and grain density be in the same unit, although the units cancel in this calculation.

\[
\text{Packing efficiency (%) = } \left(\frac{\text{Test weight (g/cm}^3)}{\text{Oat grain density (g/cm}^3)}\right) \times 100
\] (4)

Test weights were measured with a test weight filling hopper (Seedboro, Chicago, IL). For the size fractions separated by sieving, seed volumes were not adequate for the standard test weight measurements, so bulk densities were determined by measuring the volume of a measured mass of grain in a graduated cylinder.

Groat volumes and densities were measured by the same procedure as were grain volumes and densities. Grains were dehulled in a compressed air dehuller (Codema, Eden Prairie, MN). Only whole unbroken groats were used for groat volume and density measurements. Groat percentages were calculated and corrected for remaining hulled oats as described in Doehlert et al (1999).

Hull density measurements were more problematic. Because of incomplete dehulling and fine particle generation, hull mass recovered after dehulling was not considered a reliable figure for calculation of mean hull mass per grain. Instead, mean hull mass per grain was calculated as the difference between the mean grain mass and the mean groat mass. Hulls recovered after dehulling often retained their shell-like shape. Sand-displacement measurements on these hulls usually gave artificially low densities because of air spaces held within these hulls. To obtain what we felt were more reliable density values, hulls were torn into small pieces by hand, taking care to disrupt any shape that could capture air and prevent uniform sand contact with the hull pieces. Hulls were also hand-sieved on 1.7-mm mesh screens (U.S. standard testing sieve, #12 mesh) before density analysis to remove fines that were particularly difficult to manipulate during the sand-displacement measurements. Even so, it was important to humidify the air in the laboratory to reduce static interactions. Mean hull density was calculated by dividing mass of hulls used in sand-displacement procedure by the calculated volume based on sand-displacement. Mean hull volume was calculated by multiplying the mean hull mass per grain by their calculated density.

Volume determinations by the sand-displacement method were tested with steel balls 6.4 mm in diameter (McMaster-Carr, Elmhurst, IL) and with pieces of colored glass purchased from a local craft shop. Volumes of objects were confirmed using water displacement in graduated cylinders.

Grain and groat linear measurements of length, width, and area were determined by digital image analysis as described in detail in Doehlert et al (2004) with modifications described in Doehlert et al (2006). Briefly, 10-g samples of either oat grains or groats were spread on the surface of a light box next to a measuring stick. A digital photograph (5.2 megapixels) was taken with a digital camera (DSC-F707, Sony, Tokyo, Japan). Images were downloaded onto a computer and edited with PhotoShop (Adobe, San Jose, CA) photo editing software. The length scale was removed from images and pasted into a separate image for calibration. Images were converted to a gray scale and edited so that only kernels were present. Images were then analyzed with Aphelion image analysis software (Amerinex Applied Imaging, Amherst, MA). A macro written for the program generated width, length, and area measurements for each kernel in the image individually. Means of these values were used for analyses in this study.

A variety of ratios were also calculated to make various comparisons. A constant (K) was calculated to compare the relationship of oat grain width and length with grain volume. Modeling after a cylinder volume, where K would be equal to π, mean grain volume was calculated as

\[
\text{Grain volume (mm}^3) = K \times L \times (W/2)^2
\] (5)

where W was grain width, and L was grain length, both determined by digital image analysis. The equation was then solved for K, using experimentally determined grain volumes. Oat grain width-to-length ratio (OWL) was calculated from image data of oat grains. The groat volume percentage was calculated as the ratio of the groat volume and the whole grain area, multiplied by 100. The hull volume percentage was calculated as the ratio of the hull volume and the whole grain volume, multiplied by 100.
Grain was fractionated into size fractions with slotted sieves and a sizer-shaker (Seedburo, Chicago IL). Grain samples of 150 g were sieved sequentially on slotted 2.58, 2.38, and 1.98 mm sieves. All slots were 19.05 mm long. Grains held back by these sieves were labeled as large, medium, and small, respectively. Grains that passed through the 1.98-mm sieve were labeled as thin.

Experimental Design and Statistical Analysis

The field plots were arranged in a randomized complete block design with three replicates. Analyses of variance was applied to data where genotypes were considered fixed and environments were considered random. Analyses of variance were calculated with the Statistix computer package (Analytical Software, Tallahassee, FL), where the environment-by-replicate mean square was used as an error term to test the environmental effect. The genotype-by-environment interaction mean square was used to test the genotypic effect, and the genotype-by-environment interaction was tested with the residual mean square. Mean separation for genotypes was evaluated by the least significant difference, which was also calculated by the Statistix software program using the genotype-by-environment mean square as an error term. Homogeneity of variances was determined from the Bartlett’s test for equal variances before data were pooled. For correlations across genotypes, the data set derived from the size fractionation was used. Correlations were first calculated for characteristics within each environment using data from individual plots. A Chi square test was performed to verify that correlation coefficients were not significantly heterogeneous across environments (Steel et al. 1997). When heterogeneity was not observed, correlation coefficients were pooled over environments. Regressions were calculated using the data set from unfractionated (by kernel size) samples from individual plots, also with the Statistix computer package.

RESULTS

The sand-displacement method was validated by measuring volumes of objects of known density. There was a linear increase in volume of sand displaced with increasing mass of steel balls, glass pieces, oat grains, and oat groats (Fig. 1). Based on this information, we estimated the density of the steel balls to be 7.76 g/cm$^3$. Density of the glass pieces was estimated to be 2.51 g/cm$^3$, and oat groats and grains had densities of 1.258 and 0.980 g/cm$^3$, respectively. Densities of steel balls and glass pieces were confirmed by water displacement. Steel ball volume was also calculated from diameter. Based on these results, we concluded that oat grain density, based on envelope volume displacement, could be estimated by this sand-displacement method.

Test weight, oat grain mass, volume, density, and packing efficiency were measured for six oat cultivars grown at three locations in eastern North Dakota (Table I). Analysis of variance (Table II) indicated that all characteristics exhibited significant genotypic variation. All characteristics, except packing efficiency, exhibited significant environmental variation. Test weight, mean

![Fig. 1. Relationship of object mass and volume of sand displacement.](image)

**Table I**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Test Weight (g/L)</th>
<th>Mean Grain Mass (mg/grain)</th>
<th>Mean Grain Volume (mm$^3$/grain)</th>
<th>Mean Grain Density (g/cm$^3$)</th>
<th>Mean Grain Packing Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Assiniboia</td>
<td>539ab</td>
<td>37.9a</td>
<td>37.7a</td>
<td>1.013ab</td>
<td>53.2b</td>
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<tr>
<td>CDC Dancer</td>
<td>548a</td>
<td>33.5b</td>
<td>33.3c</td>
<td>1.001bc</td>
<td>54.8a</td>
</tr>
<tr>
<td>HfI</td>
<td>556a</td>
<td>33.3b</td>
<td>32.6ed</td>
<td>1.027a</td>
<td>54.2ab</td>
</tr>
<tr>
<td>Morton</td>
<td>549a</td>
<td>33.5b</td>
<td>33.1c</td>
<td>1.066ab</td>
<td>54.6a</td>
</tr>
<tr>
<td>VistA</td>
<td>530bc</td>
<td>34.1b</td>
<td>34.7b</td>
<td>0.983ed</td>
<td>53.9ab</td>
</tr>
<tr>
<td>Wabasha</td>
<td>513c</td>
<td>30.2c</td>
<td>31.2d</td>
<td>0.962d</td>
<td>53.3b</td>
</tr>
<tr>
<td>Environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Carrington</td>
<td>553a</td>
<td>35.0a</td>
<td>34.5a</td>
<td>1.014a</td>
<td>54.5a</td>
</tr>
<tr>
<td>Edgeley</td>
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<td>31.6b</td>
<td>32.7b</td>
<td>0.969b</td>
<td>53.7b</td>
</tr>
<tr>
<td>Fargo</td>
<td>545b</td>
<td>34.6a</td>
<td>34.1a</td>
<td>1.014a</td>
<td>53.7b</td>
</tr>
<tr>
<td>Mean</td>
<td>539</td>
<td>33.8</td>
<td>33.8</td>
<td>0.999</td>
<td>54.0</td>
</tr>
</tbody>
</table>

*Values in the same column (within either genotypes or environments) followed by the same letter do not differ significantly ($P < 0.05$).

**Table II**

<table>
<thead>
<tr>
<th>Source</th>
<th>Test Weight</th>
<th>Mean Grain Mass</th>
<th>Mean Grain Volume</th>
<th>Mean Grain Density</th>
<th>Mean Grain Packing Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>5,191**</td>
<td>61.1**</td>
<td>17.1**</td>
<td>0.0122**</td>
<td>4.33**</td>
</tr>
<tr>
<td>Location × replicate</td>
<td>85</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0001</td>
<td>0.98</td>
</tr>
<tr>
<td>Genotype</td>
<td>2,237**</td>
<td>55.6**</td>
<td>44.9**</td>
<td>0.0046**</td>
<td>3.89**</td>
</tr>
<tr>
<td>Genotype × location</td>
<td>335**</td>
<td>3.6**</td>
<td>1.7**</td>
<td>0.0004ns</td>
<td>1.13ns</td>
</tr>
<tr>
<td>Residual</td>
<td>83</td>
<td>0.8</td>
<td>0.7</td>
<td>0.0002</td>
<td>0.63</td>
</tr>
</tbody>
</table>

* and ** significant at $P < 0.05$ and $P < 0.01$, respectively; ns, not significant.
grain mass, and mean grain volume exhibited significant genotype-by-environment interaction. The significant interaction appeared to be due to differences in the magnitude of genotypic differences among environments, which affected genotype ranking within an environment. Test weights were high for all genotypes (Table I), indicating that all environments were favorable for production of high quality grain. Wabasha had lower test weight than all others, except for Vista. AC Assiniboia grains had greater mass than all other cultivars and Wabasha grains had less mass than all others. Mean grain volume was 31–38 mm³ estimated by sand displacement. AC Assiniboia had larger grains (by volume) than all other and Wabasha has smaller grains than all others, although it did not differ significantly from HiFi. Genotypic volume rankings were very similar to the grain mass rankings.

Mean grain density values were 1.027–0.962 g/cm³. Genotypic differences were apparent, where HiFi had the most dense and Wabasha had the least dense grains. Packing efficiency was 53.2–54.8%. Some genotypic differences were observed; CDC Dancer appeared to pack most efficiently and AC Assiniboia packed least efficiently.

To evaluate factors contributing to grain density, the oats were dehulled and the densities of the groats and hulls were determined (Table III). Significant genotypic differences were observed in grain mass and groat volume, and these were largely consistent with the genotypic differences observed in grain mass and volume (Table I). However, no significant genotypic differences were observed in groat density, which averaged ≈1.29 g/cm³. Hull mass, expressed as mg/grain, was highest in AC Assiniboia, HiFi, Morton, and Vista. CDC Dancer had lowest hull mass. Vista had the greatest hull volume and CDC Dancer had lowest hull volume. Hull density was 0.732–0.663 g/cm³. None of these characteristics exhibited any significant genotype-by-environment interaction.

Dehulling of the grain and the determination of oat and groat linear dimensions using digital image analysis (data not shown) allowed the calculation of various ratios of interest for comparison with oat grain density analyses (Table IV). CDC Dancer and AC Assiniboia had higher groat percentages than the other cultivars. The constant K, modeled after the formula for a cylinder, averaged 1.79. The oat width-to-length ratio was highest in CDC Dancer and Morton and lowest in Wabasha. The oat mass-to-area ratio was highest in CDC Dancer and lowest in Wabasha. The groat volume percentage (PCGV) was highest in AC Assiniboia and lowest in Wabasha. The hull volume percentage (PCHV) was lower in AC Assiniboia and CDC Dancer than all other cultivars tested. The PCGV and PCHV sum was consistently <100, which suggested some empty space was present with the oat hulls. The percentage of empty space within the hulls (100 - [PCGV + PCHV]) averaged 6.8, but did not vary significantly among genotypes (data not shown). To better define the effects of grain size on packing efficiency in oats, the samples were divided by width into size fractions and the grain density and size measurements of these size fractions were made (Table V).

Grand means of the six genotypes across three environments indicated that the larger grains packed less efficiently than any

### TABLE III

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Mean Groat Mass (mg/grain)</th>
<th>Mean Groat Volume (mm³/grain)</th>
<th>Mean Groat Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Assiniboia</td>
<td>29.0a</td>
<td>22.5a</td>
<td>1.288a</td>
</tr>
<tr>
<td>CDC Dancer</td>
<td>25.9b</td>
<td>19.9b</td>
<td>1.303a</td>
</tr>
<tr>
<td>HiFi</td>
<td>24.0c</td>
<td>18.7c</td>
<td>1.299a</td>
</tr>
<tr>
<td>Morton</td>
<td>24.2c</td>
<td>18.8c</td>
<td>1.284a</td>
</tr>
<tr>
<td>Vista</td>
<td>24.6bc</td>
<td>19.2bc</td>
<td>1.282a</td>
</tr>
<tr>
<td>Wabasha</td>
<td>21.9d</td>
<td>17.0d</td>
<td>1.290a</td>
</tr>
<tr>
<td>Mean</td>
<td>24.9</td>
<td>19.4</td>
<td>1.290</td>
</tr>
</tbody>
</table>

### TABLE IV

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>PG</th>
<th>K</th>
<th>OWLR</th>
<th>PCHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Assiniboia</td>
<td>76.9b</td>
<td>1.70c</td>
<td>0.28bc</td>
<td>59.7a</td>
</tr>
<tr>
<td>CDC Dancer</td>
<td>79.3a</td>
<td>1.98a</td>
<td>0.30a</td>
<td>59.8a</td>
</tr>
<tr>
<td>HiFi</td>
<td>73.9c</td>
<td>1.72e</td>
<td>0.28b</td>
<td>57.3b</td>
</tr>
<tr>
<td>Morton</td>
<td>73.5c</td>
<td>1.75bc</td>
<td>0.29a</td>
<td>56.7b</td>
</tr>
<tr>
<td>Vista</td>
<td>73.1c</td>
<td>1.81b</td>
<td>0.28bc</td>
<td>55.4bc</td>
</tr>
<tr>
<td>Wabasha</td>
<td>74.0c</td>
<td>1.77bc</td>
<td>0.27c</td>
<td>54.3c</td>
</tr>
<tr>
<td>Mean</td>
<td>75.1</td>
<td>1.79</td>
<td>0.29</td>
<td>57.2</td>
</tr>
</tbody>
</table>

a PG, groat percentage; K, constant for grain volume calculation from grain length and width (MKV = KL(W/2)²); OWLR, oat width-to-length ratio; PCHV, hull volume as a percentage of whole grain volume.

b Values in the same column followed by the same letter do not differ significantly (P < 0.05).

### TABLE V

<table>
<thead>
<tr>
<th>Size</th>
<th>Bulk Density (g/L)</th>
<th>Mean Grain Mass (mg/grain)</th>
<th>Volume (mm³/grain)</th>
<th>Density (g/cm³)</th>
<th>Packing Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>468c</td>
<td>39.5a</td>
<td>46.3a</td>
<td>0.856c</td>
<td>54.5b</td>
</tr>
<tr>
<td>Medium</td>
<td>574a</td>
<td>38.6a</td>
<td>38.8b</td>
<td>0.996a</td>
<td>57.7a</td>
</tr>
<tr>
<td>Small</td>
<td>583a</td>
<td>30.0b</td>
<td>30.0c</td>
<td>1.001a</td>
<td>58.4a</td>
</tr>
<tr>
<td>Thin</td>
<td>543b</td>
<td>18.7c</td>
<td>20.1d</td>
<td>0.931b</td>
<td>58.4a</td>
</tr>
</tbody>
</table>

a Grain samples were sieved sequentially on slotted 2.58-, 2.38-, and 1.98-mm sieves. All slots were 19.05-mm long. Grains held back by these sieves were labeled as large, medium, and small, respectively. Grains that passed through the 1.98-mm sieve were labeled as thin.

b Values in the same column followed by the same letter do not differ significantly (P < 0.05).
other grain size. Large grains also had lower bulk densities and grain densities than other size fractions. Large and medium grains had significantly greater mass than small and thin grains. Large grains had significantly greater volume than any other size fraction, and each progressive fraction differed significantly in grain volume from every other fraction (Table V).

Correlation analyses were performed for both whole grain samples and size fractions to determine possible relationships between linear size and grain volume and density. Both analyses showed similar trends, but only the analyses from the size fractions are shown. These represented a wider range of grain volumes and densities and appeared to better represent factors that affected these traits (Table VI). Bulk density was highly correlated with both grain density and the packing efficiency. Packing efficiency was negatively correlated with all measures of grain size, including grain length, width, area, volume, and mass.

Regression analysis indicated that grain density alone could account for 78% of the variation in test weight. The remaining variation would be attributed to packing efficiency (Equation 4).

**DISCUSSION**

This study used sand displacement to measure oat grain volume and density. Validation experiments indicated that the method provided good estimation of object volumes sized closely to that of oat grains. A commercial instrument called a Geopyc (Micromeretics, Norcross, GA) uses a similar approach to measure the envelope volumes and densities of porous materials, where gas pycnometry may not be appropriate. Our estimations of oat grain density averaged 0.999 g/cm³, which matched closely the estimation made by Zink (1935) using mercury displacement. We would consider sand displacement to be more satisfactory than the mercury displacement method of Zink, primarily for safety reasons, considering the toxic nature of mercury. This value is considerably lower than the absolute density value of 1.3 g/cm³ reported by Nelson (2002) determined by a gas pycnometer. Comparison of our values with that of Nelson (2002) would give an idea as to the porosity of the oat grain, or the proportion of the envelope volume accessible to the compressed air introduced by the pycnometer.

Grain volume measurements by sand displacement have considerable potential for experimental error. Frequently, air spaces can be introduced into the sand, which will cause an overestimation of volume and an underestimation of density. Also, inconsistent packing of sand routinely optimized by tapping the measuring cup on the bench, can also lead to errors in volume estimations. These errors are reduced with operator experience, but we found that four determinations per sample reduced experimental error, or allowed recognition of erroneous values. Oat grain volume determination with 25 g of sample generally yielded coefficients of variation (CV) values of 0.5-2%. Great samples with 15-20 g yielded CV values of 2-4%, and hull determination with 4-5 g of sample yielded CV values of 5-10%. Also, the larger samples (≤25 g) generated less error than the smaller samples (<10 g).

Two earlier studies (Murphy 1962; Root 1979) measured oat groat density using liquid displacement. They both estimated the groat density to be ≈1.35 g/cm³ and found no genotypic or environmental variation in these values. We have also measured groat density by liquid displacement (water or acetone) and obtained similar results as reported by Root (1979) and Murphy (1962) with samples unrelated to those used in this current study. Because liquid is rapidly absorbed by groats, we suggest that liquid displacement overestimates groat density. The values of groat density (≈1.29 g/cm³) that we obtained by sand displacement are similar to values of wheat density obtained by oil displacement method used by Martin et al (1979).

Packing efficiency values for oat samples (53–55%) seem to differ from the values reported by Zink (1935) for oats of 44.5–52.4%. We can offer no explanation for this difference. Our oat packing efficiency values are similar to those reported for wheat (Zink 1935; Yamasaki and Briggle 1969). Correlation analysis suggested that grain size affected packing efficiency and as well as suggesting that smaller grains packed more efficiently. This is consistent with concepts forwarded by Symons and Fulcher (1988) that rounded kernels improved test weight by improving packing. The trends in packing efficiency of size fractions were largely consistent with the trends found in the unfractonated samples. Regression of test weight data indicated that 78% of the variation in bulk density could be accounted for by grain density. Thus, results suggest that only ≈20% of the total variation in test weight in the samples analyzed can be attributed to packing efficiency. It should be noted that all of these samples would be considered to have high test weight according to grain grading protocols (USDA 1978).

We would consider that most of the samples analyzed here had close to maximal grain fill. We would expect that in samples with poorer grain fill, where groat size is relatively small in comparison to the grain size, as described in Doehlert et al (2006), a much larger proportion of the test weight variation would be attributed to grain density. It would appear that grain packing is a relatively minor factor affecting oat test weight. This is consistent with ideas forwarded by Hlynka and Bushuk (1959). In contrast, findings in wheat indicated that packing efficiency was the major factor affecting test weight (Troccoli and deFonzol 1960; Yamasaki and Briggle 1969; Ghaideri et al 1971). The presence of the hull in oats is likely to contribute heavily to this difference, in that there was relatively little variation in oat groat density.

We would not suggest that packing efficiency of oats cannot be improved. Analyses of Donev et al (2004) suggested that spheres with uniform sizes have a packing efficiency of ≈62% and oblate ellipsoids could pack with an efficiency of ≈74%. In that the highest values observed in this study for oat grain packing efficiency was 58%, theoretically, significant improvements could be made in packing efficiency for oat grains.

Significant differences in grain density were found (Table I), yet no significant differences in groat density were found, and only minor differences in hull densities were observed (Table III).
Correlations between test weight and groat percentage have been recognized (Pomeranz 1962; Doehlert et al 2000). Our results indicate that grains with a higher mass proportion of groat to hull will be denser, and this would contribute to greater test weights. It is also interesting to observe that the sum of the groat volume and hull volume were consistently less than the volume of the whole grain. We presume this difference is empty space. Obviously, empty space within the oat hull could profoundly affect test weight, but no significant variation in this value could be detected.

Analysis of variance indicated significant genotypic and environmental variation, as well as significant genotype-by-location interactions in many components of test weight. It should be emphasized that nearly all of the samples analyzed here would be considered of high test weight. Only a small portion of the expected variation in test weight is represented by this data set. Therefore, we would limit interpretations of the genotype-by-environment interactions in the test weight components until a data set is obtained that includes more diverse environmental conditions.

The oat grain width to length ratio (OWLR) was positively correlated with test weight (Table VI). Studies with wheat have indicated that this characteristic has a profound effect on packing efficiency and Symons and Fulcher (1988) suggested that correlations of test weight with the oat width-to-length ratio were also due to a packing effect. Our study here indicated that OWLR was correlated with both packing efficiency and with mean grain density. This suggested that not only may grains with larger width length ratios pack more efficiently, but this shape of grains appears to be denser as well. Thus, a combination of increased density and improved packing appears to result in the associated increase in test weight.

The empirical measurement of oat grain volume along with the linear measurements of grain size allow for comparison of grain shape with a cylinder, as described by Ghaderi et al (1971). The values for constant $K$ (Table III) would be equal to $\pi (3.14159...)$ if the grains were perfect cylinders. Our observations indicated that $K$ averaged 1.79, which is closer to one-half $\pi$. Therefore, oat grains may more closely resemble semi-cylinders in shape.

A common goal of oat breeding is to produce genetic lines that consistently generate high test weight grain. The results presented here suggest that selection for high density grain could accomplish this goal. Improved grain density is also likely to result in improved groat percentage because of the density differences between the groat and hull. Whereas sand displacement is useful in applications where the components of test weight are being studied, or in situations where it might be suspected that both grain density and packing efficiency vary, for most applications, especially in the routine selection of oat line for grain quality, the traditional test weight measurement remains the most useful estimate of grain density because of its simplicity and the relative consistency of packing efficiency among oat grain samples.

**CONCLUSIONS**

We have used a sand-displacement method to measure oat grain density to determine the physical basis of test weight in oats. Analyzing a set of high test weight samples, we determined that $\approx 78\%$ of variation in test weight could be attributed to variation in oat grain density. The remaining variation would be attributed to packing efficiency. Oat grain density averaged $0.999 \text{ g/cm}^3$. Packing efficiency averaged 54%. Groat density averaged 1.29 g/cm$^3$, and hull density averaged 0.69 g/cm$^3$. The density differences between groat and hull provides a mechanism by which groat percentage would affect test weight. The sum of the groat volume and hull volume was consistently less than the grain volume, suggesting the presence of empty space within the hulls.

**LITERATURE CITED**


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