# TECHNICAL NOTE:

# FIELD-OBSERVED ANGLES OF REPOSE FOR STORED GRAIN IN THE UNITED STATES

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**ABSTRACT.** *Bulk grain angle of repose (AoR) is a key parameter for inventorying grain, predicting flow characteristics, and designing bins and grain handling systems. The AoR is defined for two cases, piling (dynamic) or emptying (static), and usually varies with grain type. The objective of this study was to measure piling angles of repose for corn, sorghum, barley, soybeans, oats, and hard red winter (HRW) wheat in steel and concrete bins in the United States. Angles were measured in 182 bins and 7 outdoor piles. The piling AoR for corn ranged from 15.7° to 30.2° (median of 20.4° and standard deviation of 3.8°). Sorghum, barley, soybeans, oats, and HRW wheat also exhibited a range of AoR with median values of 24.6°, 21.0°, 23.9°, 25.7°, and 22.2°, respectively. Angles of repose measured for the seven outdoor piles were within the ranges measured for the grain bins. No significant correlation was observed between AoR and moisture content within the narrow range of observed moisture contents, unlike previous literature based on laboratory measurement of grain samples with wider ranges of moisture content. Overall, the average measured piling AoR were lower than typical values cited in MWPS-29, but higher than some laboratory measurements.*

**Keywords.** *Angle of repose, Moisture, Grain bins, Corn, Wheat, Sorghum, Barley, Soybeans, Oats*

Angle of repose (AoR, °), sometimes referred to as cone angle or slope angle, is one of the key parameters for measuring and evaluating grain storage systems, including grain bins and outdoor piles. AoR is a critical design and management consideration for grain bins because the shape of the grain pile, indicated by its AoR, affects storage capacity, aeration system design and performance, and grain pressure on the walls of grain silos (Pierce and Bodman, 1987). In addition to grain storage applications, AoR is also used frequently to determine the flow characteristics and propensity for flow problems for powders and bulk grain products (Carr, 1965; Bhadra et al., 2009).

AoR is defined as the angle formed between the slope of the pile and a horizontal plane when the pile is stationary (Mohsenin, 1986). Two types of AoR (static and dynamic) are commonly associated with bulk grain. Static AoR is the angle measured from the horizontal at which the material will begin to slide and or roll upon itself after it has been allowed to 'consolidate' or remain static. Dynamic AoR is the angle that the granular material makes with the horizontal when the granular material comes to rest after sliding and or rolling upon itself in an 'unconsolidated' or loose form (Mohsenin, 1986). Hence, static AoR is also referred to as emptying or funneling, while dynamic AoR is also referred to as filling or piling (Stahl, 1950). The dynamic AoR is generally smaller, by 3° to 10°, than the static AoR (Fowler and Wyatt, 1960). Also, dynamic AoR (or filling AoR) is the most common physical property that is used for material handling systems and bin deigns (Anderson and Bern, 1984). AoR is commonly measured using the discharge method, the tilting method, or the injection method (Linoya et al., 1990; Kalman et al., 1993).

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However, Kurkuri et al. (2012) suggested that the problem with measuring AoR using the traditional method (from grain height on table top) is that it assumes the cone pile to be ideally symmetrical with a straight slope when, in fact, the piles are cone-shaped with a slight truncation of the cone top. Kurkuri et al. (2012) used photographic analysis software to measure AoR for wheat and discovered that the new image analysis method showed AoR values of 11.7° to 15.4° greater than traditional methods. Bhadra et al. (2009) used a powder tester that utilized a laser to scan the surface of distillers grain (a coproduct from corn based bioethanol industry) on a circular plate and calculate the AoR but did not find any significant difference between AoR values found by laser method vs. traditional table top method for distillers grain samples.

The most widely cited data for AoR relevant to food grain, such as wheat, corn, soybean kernels, oats, sunflower seeds, and canola, are reports from Stahl (1950), Lorenzen (1959), Pierce and Bodman (1987), Mohsenin (1986), and Molenda and Horabik (2005). A review by Boac et al. (2010) found wide ranges of AoR values for most field crops including HRW wheat and yellow corn. However, sometimes variations from the average values of AoR found in the literature are observed in bulk grain stored in commercial bins. AoR in the literature is largely from laboratory measurements so there is little information available on any variability due to field conditions in grain bins. Pierce and Bodman (1987) provided the only field measured AoR dataset found in the literature for grain in storage systems. Also, MWPS-29 (1999) lists ranges of AoR that were likely from field measurements—some of the values in MWPS-29 match the results of Pierce and Bodman (1987) exactly, while others do not match.

Herman et al. (1998) calculated outdoor pile capacity for corn with two AoR values (22° and 27°), but they assumed zero compaction and no grain pile stress on sidewalls. Similarly, Hellevang (2007) calculated capacities for wheat, soybean, and corn piles with AoR for wheat and soybean as 25° and corn as 23° without considering the effect of grain compaction in outdoor piles.

Therefore, the objective of this research was to measure the piling AoR for major U.S. grains stored in bulk in on-farm and commercial storage bins constructed of steel and concrete and in outdoor piles. A few emptying AoR values were also obtained during the study.

# MATERIALS AND METHODS

## MEASUREMENT OF ANGLE OF REPOSE

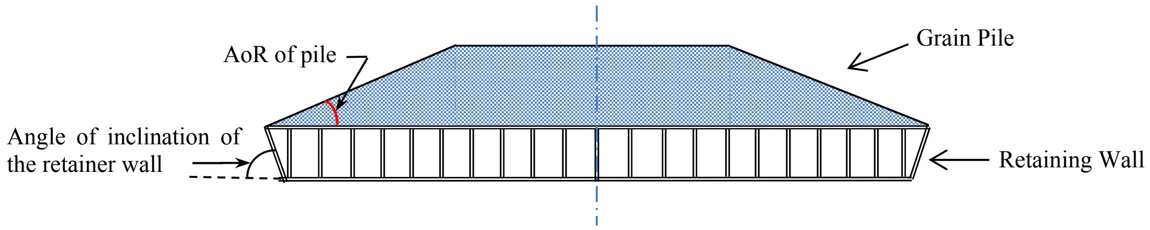
AoR was measured in conjunction with determining grain profiles in on-farm and commercial bins in the United States from 2010 to 2013 for six crops: hard red winter (HRW) wheat, corn, soybeans, oats, barley, and sorghum. The grain piling AoR was measured using a Leica Disto D8 laser distance meter (Leica Geosystems AG, St. Gallen, Switzerland). Accuracy of the tilt sensor in the laser distance meter was ±0.1°. The AoR of the grain surface was determined by averaging seven data points evenly spaced between the bin sidewall and the top of the grain cone (if coned up) or to the bottom of the cone (if coned down). For cone-down grain bins, the AoR was referred to emptying AoR. The AoR was calculated using the distance and angle data from the Leica Disto laser meter when projected onto the grain surface through an accessible side or top manhole of the grain bin. Details regarding grain bin diameter, bin height, crop type, bin wall type, moisture content, and test weight were either measured or collected from the farmer or grain elevator managers. For flat surface profiles the angle of the surface is near zero, which does not represent a true AoR, and those cases were not included in this study. These flat profiles usually arise from using a grain spreader to produce a nearly flat surface inside the bin (common in metal bins) or from partially unloading from the bottom of those bins, producing a shallow cone angle on top (common in concrete bins).

The other frequently used method to store grain is outdoor piles. Elevator operators typically utilize outdoor storage of grain through piling as a temporary strategy when crop production is higher than average (Herrman et al., 1998). However, increased productivity and improved outdoor storage facilities have triggered more frequent instances of outdoor piling over the last two decades and it has become a standard part of many modern grain storage systems. Outdoor piles are typically filled by tractor-powered portable conveyors, resulting in elongated triangular-shaped piles with semicircular ends, as shown in figure 1. Volume measurement of outdoor piles requires profiling of the grain surface, which produces an accurate calculation of the average AoR for the pile.

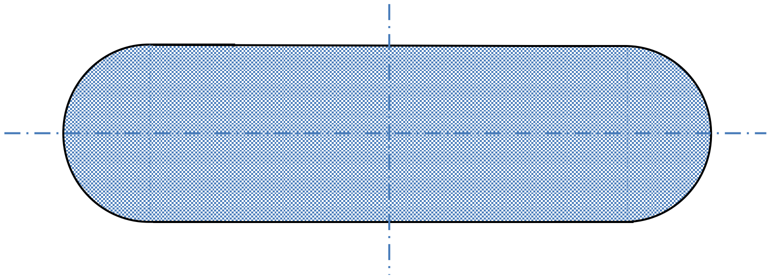
AoR for outdoor piles (also commonly known as bunkers) was also measured using a Leica Disto D8 laser meter (Leica Geosystems AG, St. Gallen, Switzerland). The laser meter measured the angle of the pile slopes' inclination at multiple points, and then the average AoR of the pile was calculated. The Leica Disto D8 was placed on the edge of the pile (fig. 1, enlarged view) and the unit's laser beam was pointed toward the peak of the pile. For accuracy, the magnifying camera view of the meter was used to pinpoint the peak of the grain pile. Once the peak of the pile was located, the angle function on the meter was used to obtain the AoR. The AoR on each elongated side was measured at eight points equally spaced along the length of the pile, whereas three equally spaced AoR were measured on each of the semicircular ends. Thus all AoR values measured in this study of the grain profile in piles and bins eliminated the possible differences found by Kurkuri et al. (2012) for small piles in a laboratory setting.

Significant differences between AoR values with a 95% confidence interval were determined using the Tukey-Kramer multiple comparison procedure with SAS® 9.2 software (Cary, N.C.). Significant differences between semi-circular end and sloped side AoR for each location is represented by different letters in table 2. The significant differences for average AoR among location for each crop type is represented by different numbers in (table 2).

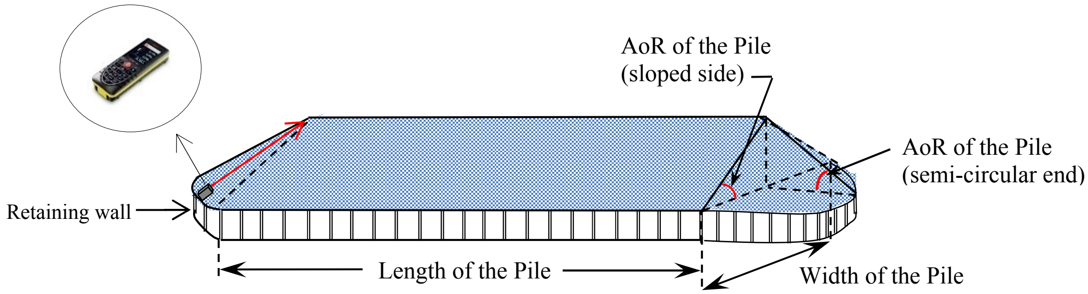
The moisture content values from the piles reported in this study were obtained from the elevators. Elevators typically use Federal Grain Inspection Service (USDA-



**(a) Side view of an outdoor pile**



**(b) Top view of an outdoor pile showing the linear section and semi-circular ends**



**(c) Schematic showing the ends of the grain pile are sloped and semicircular in shape. The Leica Disto D8 is enlarged in the inset diagram.**

**Figure 1. Outdoor pile with a retaining wall (not to scale).**

GIPSA, 2009) standard methods to measure moisture content with a dielectric moisture meter.

## RESULTS AND DISCUSSION

Tables 1, 2, 3, and 4 provide summaries of bin dimension, test weight [the bulk density of the grain measured using Federal Grain Inspection Service (FGIS) procedures], moisture content (%, wb), and AoR values observed for corn, sorghum, barley, soybean, oats, and HRW wheat measured in storage bins and outdoor piles. The medians of test weight and moisture content for corn (741 kg/m$^3$ and 14.60%, wb) and sorghum (759 kg/m$^3$ and 11.5%, wb) were within the usual ranges reported in Henderson and Perry (1976), Mohsenin (1986), Nelson (2002), Molenda and Horabik (2005), and *ASABE Standards* (2006). Bin diameter and eave height covered a wide range because AoR data and subsequent grain profile measurements were obtained from many sizes of on-farm and commercial grain elevator bins. Bin diameters ranged from 3.59 to 31.9 m and 4.56 m to 27.1 m for corn and sorghum, respectively.

The median AoR for corn during piling was 20.4° (table 1), with a range of 15.7° to 30.2° for corrugated steel and concrete bins. This median value of AoR was higher than the average AoR (16.0° for piling AoR) found by Stahl (1950) but very close to the average value of 21° in MWPS-29 (1999). The range for piling AoR of corn listed in MWPS-29 (1999) was 21° to 26°, which was essentially the same as the range of 20.7° to 26.1° for corn reported by Pierce and Bodman (1987), both of which overlap with the wider range in this study (minimum 15.7° to maximum 30.2°). In one steel bin that was partially unloaded we measured an emptying AoR of 23.0°. This value was similar to Stahl's (1950) AoR reported value of 27°. No additional cases of emptying AoR for corn were found to compare to the emptying AoR values from Lorenzen (1959) for corn (35° to 38.5°).

For sorghum the median AoR for piling was 24.6° (table 1), which is higher than the 20° value reported by

**Table 1. Summary of AoR, bin dimensions, test weight, and moisture content for corn and sorghum[a].**

| | Bin Diameter (m) | Eave Height (m) | TW (lb/bu) | TW (kg/m$^3$) | MC (%, wb) | Piling AoR (°) |
|---|---|---|---|---|---|---|
| CORN | | | | | | |
| Median | 9.85 | 11.1 | 57.6 | 741.0 | 14.6 | 20.4 |
| Mean | 12.4 | 12.5 | 57.7 | 743.0 | 14.6 | 21.4 |
| Max | 31.9 | 31.4 | 60.0 | 772.0 | 17.2 | 30.2 |
| Min | 3.59 | 4.43 | 54.5 | 701.0 | 13.0 | 15.7 |
| Std DV-S | 6.49 | 7.53 | 1.23 | 15.8 | 0.80 | 3.78 |
| CV | 0.52 | 0.60 | 0.02 | 0.02 | 0.05 | 0.18 |
| Location | Kansas, Minnesota, Iowa, Kentucky, North Dakota, Michigan, Colorado, Texas | | | | | |
| Type of bin | 50 steel (corrugated), 2 concrete; 52 total bins | | | | | |
| Special cases of AoR | 1 emptying AoR at 22.95°; 1 apparent AoR at 1.9°, 7 flat top (AoR =0°) for steel bins | | | | | |
| Total outdoor piles | 6; 3 with straight edge concrete retainer wall and two with inclined steel wall with inclination angle at 51.1° and 58.6° and one with no retaining wall. | | | | | |
| SORGHUM | | | | | | |
| Median | 7.62 | 29.2 | 59.0 | 759.0 | 11.5 | 24.6 |
| Mean | 10.3 | 27.1 | 58.6 | 754.0 | 12.1 | 24.0 |
| Max | 27.1 | 42.7 | 59.0 | 759.0 | 14.6 | 28.7 |
| Min | 4.56 | 12.4 | 57.5 | 741.0 | 9.80 | 15.5 |
| Std DV-S | 6.90 | 7.99 | 0.56 | 7.14 | 1.60 | 3.32 |
| CV | 0.67 | 0.30 | 0.01 | 0.01 | 0.13 | 0.14 |
| Location | Kansas, Oklahoma, Texas | | | | | |
| Type of Bin | 5 steel (corrugated), 5 concrete interstice, 8 concrete; 18 total bins | | | | | |
| Special cases of AoR | 4 emptying AoR with average of 24.60°; 2 apparent AoR with average of 3.0° | | | | | |
| Total outdoor piles | 1 with no retainer walls | | | | | |

[a] TW is test weight usually measured by FGIS guidelines in lb/bu; MC is moisture content in % wb; AoR is angle of repose (°); Std DV- S is standard deviation measured using sample size; CV is coefficient of variation (std. DV/mean).

Stahl (1950) but lower than the 31° to 33.5° range of values reported by Lorenzen (1959). The average AoR for emptying with sorghum was found to be 24.60°, which is lower than the emptying AoR of 33° reported by Stahl (1950), lower than the 35° to 38.5° range of values reported by Lorenzen (1959), and lower than the average of 29° in MWPS-29 (1999). The range for sorghum piling AoR listed in MWPS-29 was 27° to 33°, while the range was reported as 27.1° to 30.9° in Pierce and Bodman (1987). These ranges slightly overlap with the range in this study, which had a lower minimum (15.5°) and maximum (28.7°) than those two references. Measured sorghum bins included a mix of corrugated steel, concrete interstice, and concrete round bins.

Seven AoR values from outdoor flat storage piles for corn and sorghum are shown in table 2. The range of AoR values for three corn piles was 18.1° to 20.9°, which was within the range of filling AoR values measured for corn bins (table 1). Moisture contents of the corn piles ranged from 14.4% to 17.0%, mostly higher than the median value (14.6%, wb) of moisture in 52 corn bins and piles combined (table 1). For these corn piles the test weight ranged from 733.6 to 749.1 kg/m$^3$, well within the range measured in corn bins. The single sorghum pile had a typical value for moisture content, 13.3% (wb), similar to moisture contents for sorghum bins. For the sorghum pile the average AoR was 27.10°, which was well within the range of AoR values found in sorghum bins. Statistically significant differences were found between the AoR averages for the three locations (table 2) for corn piles using the Tukey-Kramer multiple comparison procedure. Only locations 1 and 4c (table 2) showed significant difference between semi-circular end AoR and sloped side AoR ($p < 0.05$). This might have occurred because outdoor piles are formed using conveying systems, which could slightly disturb the sides as the grain conveyor moves forward to complete the pile, resulting in a smaller angle. But the semicircular ends of the pile (fig. 1) do not see as much disturbance from the movement of the conveyor.

The median piling AoR for barley (21.0°, table 3) was higher than the 16° value reported by Stahl (1950), but lower than the 30.0° to 33.5° range of values reported by Lorenzen (1959) and the 28° average in MWPS-29 (1999). The range for piling AoR listed in MWPS-29 was 24° to 34° for barley, which was entirely higher than the range observed in this study. Most of the barley bins were from the same

**Table 2. Summary of angle of repose, pile dimensions, and crop quality, for outdoor piles.[a]**

| Location | Retaining Wall Angle (°) | Crop | Average Piling AoR (Semi-circular end) (°) | Average Piling AoR (Sloped side) (°) | Average Piling AoR (°) | Pile Capacity (m$^3$) | Average Moisture (%, wb) | Average Test Weight (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 90 | Corn | 21.6 a | 20.2 b | 20.9$^{1}$ | 31,146. | 16.0 | 733.6 |
| 2 | 51.1 | Corn | 19.6 a | 19.4 a | 19.5$^{2}$ | 21,052. | 17.0 | 733.6 |
| 3 | 58.6 | Corn | 18.6 a | 18.1 a | 18.3$^{3}$ | 13,358. | 16.0 | 746.5 |
| 4a | N.A. | Corn | 18.1 a | 18.10 a | 18.1 $^{3,4}$ | 8,304. | 14.4 | 746.4 |
| 4b | 90 | Corn | 18.8 a | 18.66 a | 18.69$^{3}$ | 5,707. | 14.9 | 749.1 |
| 4c | 90 | Corn | 17.6 a | 18.46 b | 18.24 | 7,050. | 15.0 | 746.4 |
| 5 | N.A. | Sorghum | 27.4 a | 26.8 a | 27.1 | 5,471. | 13.3 | 753.3 |

[a] For no retaining wall type, the retaining wall height is non-existent. Straight-edged retaining wall is concrete and slanted edge is made of steel. Same letters for AoR represents no statistical difference between semi-circular ends and sloped side at alpha = 0.05, within each location. Same number superscript represents no statistical difference among location for average AoR for corn piles at alpha = 0.05. N.A. indicates there was no retaining wall.

**Table 3. Summary of AoR, bin dimensions, test weight, and moisture content for barley and soybeans[a].**

| | Bin Diameter (m) | Eave Height (m) | TW (lb/bu) | TW (kg/m$^3$) | MC (%, wb) | Piling AoR (°) |
|---|---|---|---|---|---|---|
| BARLEY | | | | | | |
| Median | 27.0 | 20.1 | 51.5 | 663.0 | 9.85 | 21.0 |
| Mean | 21.9 | 23.3 | 51.0 | 657.0 | 9.80 | 20.8 |
| Max | 32.0 | 34.4 | 52.0 | 669.0 | 10.2 | 23.7 |
| Min | 6.10 | 18.3 | 49.0 | 631.0 | 9.50 | 15.3 |
| Std DV-S | 9.32 | 6.14 | 1.08 | 13.8 | 0.29 | 2.33 |
| CV | 0.43 | 0.26 | 0.02 | 0.02 | 0.03 | 0.11 |
| Location | Montana, Idaho | | | | | |
| Type of Bin | 9 steel corrugated, 3 concrete; 12 total bins | | | | | |
| Special cases of AoR | No emptying AoR, 2 flat top (AoR =0°) for steel bins | | | | | |
| SOYBEANS | | | | | | |
| Median | 11.0 | 7.73 | 58.2 | 749.0 | 9.50 | 23.9 |
| Mean | 11.9 | 9.56 | 58.3 | 750.0 | 9.35 | 23.8 |
| Max | 22.9 | 22.8 | 61.0 | 785.0 | 11.0 | 28.6 |
| Min | 4.27 | 3.97 | 56.4 | 726.0 | 8.14 | 18.2 |
| Std DV-S | 5.03 | 5.02 | 1.18 | 15.1 | 0.76 | 2.57 |
| CV | 0.42 | 0.53 | 0.02 | 0.02 | 0.08 | 0.11 |
| Location | South Dakota, North Dakota, Minnesota, Kansas | | | | | |
| Type of Bin | 21 steel corrugated | | | | | |
| Special cases of AoR | No emptying AoR, 1 apparent AoR at 11.0° | | | | | |

[a] TW is test weight usually measured by FGIS guidelines in lb/bu; MC is moisture content in % wb; AoR is angle of repose (°); Std DV- S is standard deviation measured using sample size; CV is coefficient of variation (std. DV/mean).

geographic region of the United States and the average MC was low at 9.8%. All of the barley measured was of malting barley varieties. Similarly to barley, the median piling AoR for soybeans (23.9°, table 3) was higher than the average AoR (16°) found by Stahl (1950), but slightly lower than the 25° average in MWPS-29 (1999). The range for piling AoR of soybeans listed in MWPS-29 was 22° to 29°, which largely overlaps with the range in this study (minimum 18.2° to maximum 28.6°). No instances of emptying AoR were measured for barley and soybeans.

The median AoR for oats (25.7°, table 4) was higher than the piling AoR of 18° reported by Stahl (1950), but lower than the average value of 28° in MWPS-29 (1999). The range for piling AoR listed in MWPS-29 was 24° to 32° for oats, which overlaps with this study, but with a higher minimum and maximum than observed in this study (minimum 19.7°, maximum 29.4°). No emptying AoR cases were observed for oat bins. The piling AoR values for HRW wheat in this study were from almost equal numbers of concrete and corrugated steel bins. The median piling AoR for HRW wheat was 22.2°, which was higher than the average AoR (16°) reported by Stahl (1950), lower than the range of values (29.5° to 35.0°) reported by Lorenzen (1959) for wheat (no class reported), and lower than the average of 25° in MWPS-29 (1999) for Hard Red Spring (HRS) wheat. The range for piling AoR listed in MWPS-29 was 19° to 38° for HRS wheat, which was a narrower range than observed in this study for HRW wheat. The 25° average value for piling AoR listed in MWPS-29 was very close to the average of 24.3° in this study as shown in table 5. For HRW wheat the emptying AoR was measured in three different bins with an average value of 21.0°, which was lower than the value reported by Stahl (1950) (27° for emptying AoR).

Because MWPS-29 (1999) cites field-relevant values of AoR for design use, it was expected that the field

**Table 4. Summary of AoR, bin dimensions, test weight, and moisture content for oats and HRW wheat[a].**

| | Bin Diameter (m) | Eave Height (m) | TW (lb/bu) | TW (kg/m$^3$) | MC (%, wb) | Piling AoR (°) |
|---|---|---|---|---|---|---|
| OATS | | | | | | |
| Median | 9.30 | 33.9 | 42.0 | 541.0 | 12.4 | 25.7 |
| Mean | 11.0 | 32.5 | 42.2 | 543.0 | 12.4 | 25.8 |
| Max | 27.3 | 37.8 | 47.5 | 611.0 | 13.2 | 29.4 |
| Min | 4.09 | 25.7 | 39.3 | 506.0 | 11.8 | 19.7 |
| Std DV-S | 6.94 | 3.48 | 2.06 | 26.5 | 0.33 | 2.07 |
| CV | 0.63 | 0.11 | 0.05 | 0.05 | 0.03 | 0.08 |
| Location | Iowa, Nebraska | | | | | |
| Type of Bin | 3 steel corrugated, 3 concrete interstice, 17 concrete round; 23 total bins | | | | | |
| Special cases of AoR | No emptying AoR, no flat top (AoR = 0°) | | | | | |
| HARD RED WINTER WHEAT | | | | | | |
| Median | 4.57 | 37.2 | 60.1 | 774.0 | 11.6 | 22.2 |
| Mean | 8.24 | 29.8 | 59.8 | 770.0 | 11.5 | 24.3 |
| Max | 31.9 | 42.0 | 62.4 | 803.0 | 13.1 | 43.4 |
| Min | 4.56 | 3.05 | 52.7 | 678.0 | 10.0 | 15.6 |
| Std DV-S | 7.06 | 14.6 | 1.69 | 21.8 | 0.67 | 6.67 |
| CV | 0.86 | 0.49 | 0.03 | 0.03 | 0.06 | 0.27 |
| Location | Kansas, Oklahoma, Texas | | | | | |
| Type of Bin | 29 steel corrugated, 27 concrete round; 56 total bins | | | | | |
| Special cases of AoR | 3 emptying AoR with average of 20.97°; 1 steel bin jagged top, 1 steel bin with flat top (AoR =0°), 7 apparent AoR with average of 6.87° (range = 1.82° to 9.62°; median = 8.95°) | | | | | |

[a] TW is test weight usually measured by FGIS guidelines in lb/bu; MC is moisture content in % wb; AoR is angle of repose (°); Std DV- S is standard deviation measured using sample size; CV is coefficient of variation (std. DV/mean). ; HRW wheat is Hard Red Winter Wheat.

**Table 5. Comparison of measured AoR with MWPS-29 (1999).**

| | Average AoR | Median AoR | Average MC[a] | Minimum AoR | | Maximum AoR | | Percent Difference[b], AoR | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Grain | MWPS-29 | This Study | This Study | MWPS-29 | This Study | MWPS-29 | This Study | Average vs Median | Min. | Max. |
| Barley | 28 | 21.0 | 9.8 | 24 | 15.3 | 34 | 23.7 | -29% | -44% | -36% |
| Corn | 23 | 20.4 | 14.6 | 21 | 15.7 | 26 | 30.2 | -12% | -29% | +15% |
| Oats | 28 | 25.7 | 12.4 | 24 | 19.7 | 32 | 29.4 | -9% | -20% | -8% |
| Sorghum | 29 | 24.6 | 12.1 | 27 | 15.5 | 33 | 28.7 | -16% | -54% | -14% |
| Soybeans | 25 | 23.9 | 9.4 | 22 | 18.2 | 29 | 28.6 | -4% | -19% | -1% |
| Hard wheat[c] | 25 | 22.2 | 11.5 | 19 | 15.6 | 38 | 43.4 | -12% | -20% | +13% |

[a] No MC values reported for MWPS-29.

[b] Percent difference is calculated as the difference of the AoR values between this study and MWPS-29 and negative and positive percent represents lower than MWPS-29 and higher than MWPS-29 values, respectively.

[c] MWPS-29 reported hard red spring; this study measured hard red winter.

measurements in this study might agree well with those values. MWPS-29 reported only mean AoR values; however, as in the discussions above, we have reported our median values for comparison. This was done because the differences between the median and mean value for two crops, corn and HRW wheat (tables 1 and 4), indicate those data had non-normal distributions. Thus our median values for corn and wheat are the most appropriate for comparing to other representative values such as the data in MWPS-29, in which, apparently, the mean values were the most appropriate for comparison. We used medians for all six crops for consistency and have additionally reported means standard deviations, minima, and maxima for all crops (tables 1, 3, and 4).

There were several differences in the minimums and maximums for the ranges measured compared to MWPS-29 as seen above for the piling AoR values (table 5), with the largest differences being lower minimum values for all grains—at least 19% to 20% lower (oats, soybeans, and wheat) and as much as 54% lower (sorghum). It may be that we observed cases that had no obvious disturbance to the surface that would have reduced the apparent AoR, but there may have been small disturbances that were not reported to us. The measured surfaces were loaded and sat for an average of about one week, but up to a month for a few cases, before being measured.

All of the maximum values in this study were within 15% of those in MWPS-29 (1999) except for barley which was 36% lower than in MWPS-29 (table 5). Other than for barley, the average values in this study were all lower, but within 19% of the average values in MWPS-29. The average for barley in this study was 30% lower than the average in MWPS-29 (table 5). The moisture contents of the samples in MWPS-29 were not mentioned, but they would be expected to be in the normal storage moisture content range and so, while differences in moisture content may account for the smaller differences seen, that seems unlikely to be the cause of larger differences except in the case of barley. The low average MC of the measured barley may be the reason for lower average AoR for barley than reported in MWPS-29. Unknown disturbance of surfaces could account for some of the lower minimum and median values observed here, but it seems unlikely that so many of the lower values were from slightly disturbed surfaces that were not reported to us and almost entirely for cases where no disturbance would be expected.

In the literature, some studies have looked at the effect of moisture content on AoR. Lorenzen (1959) determined that an increase in moisture content produced small changes in the piling AoR values for milo (moisture content from 8% to 22%, wb) and produced larger changes in piling AoR for corn (moisture content from 8 to 23%, wb), wheat (moisture content from 8% to 19%, wb), and barley (moisture content varied from 8% to 23%, wb). Tabatabaeefar (2003) determined that a linear correlation ($R^2$ of 0.80) existed between piling AoR and changes in moisture content for Iranian wheat varieties. Increasing moisture contents from 0 to 22% (db) or 0 to 18% (wb), increased piling AoR from 34.5° to 45°. Benedetti and Jorge (1991) determined that the piling AoR values for wheat increased from 31.7° to 38.2° for an increase in moisture content from 10% to 25% wb. Fowler and Wyatt (1960) theorized that variation of angle of repose with moisture content is due to the surface layer of moisture surrounding each grain and that surface tension effects become predominant in holding aggregates of grain together. Seifi and Mardini (2010) also found correlation between moisture (4.73 to 22%, wb) and static AoR for corn samples. We measured 182 bins of different types with six different grain types. No correlation was found for any crops with respect to changes in moisture content for the AoR values listed in tables 1 to 4. Grain in the United States is stored over a narrow range of moisture contents. Piling AoR values for HRW wheat varied only over a range of moisture contents of from 10% to 11.56% d.b. (table 4), not wide enough to see a correlation between moisture and AoR. Similarly, for the other crops, narrow ranges of moisture content found in field samples were not sufficient to determine any correlation between AoR and moisture content.

## CONCLUSIONS

The following conclusions were drawn from this research:

1. The median AoR values for piling in storage bins and outdoor piles for corn, sorghum, barley, soybeans, oats, and HRW wheat were 20.4°, 24.6°, 21.0°, 23.9°, 25.7°, and 22.2°, respectively. The piling AoR values found in this study were lower than many values reported elsewhere, but higher than some reported laboratory measurements.

2. No correlation was found between piling AoR and moisture content, likely due to the limited ranges of the moisture contents observed in these field measurements.

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## REFERENCES

*ASABE Standards*. (2006). D241.4: Density, specific gravity, and mass-moisture relationships of grain for storage. St. Joseph, MI: ASABE.

Benedetti, B. C., & Jorge, J. T. (1991). Effect of moisture content on coefficients of friction and angle of repose for different types of grains. *Proc. 5th Int. Working Conf. on Stored-Product Protection.* Retrieved from http://spiru.cgahr.ksu.edu/proj/iwcspp/pdf2/5/1777.pdf

Bhadra, R., Muthukumarappan, K., & Rosentrater, K. A. (2009). Flowability properties of commercial distillers dried grains with solubles. *Cereal Chem. J., 86*(2), 170-180. http://dx.doi.org/10.1094/CCHEM-86-2-0170

Boac, J. M., Casada, M. E., Maghirang, R. G., & Harner III, J. P. (2010). Material and interaction properties of selected grains and oilseeds for modeling discrete particles. *Trans. ASABE, 53*(4), 1201-1216. http://dx.doi.org/10.13031/2013.32577

Fowler, R. T., & Wyatt, F. A. (1960). The effect of moisture content on the angle of repose of granular solids. *Australian J. Chem. Eng., 1*, 5-8.

Hellevang, K. (2007). Ground pile design and management. Fargo, ND: North Dakota State University Extension Service.

Henderson, S. M., & Perry, R. L. (1976). *Agricultural Process Engineering* (3rd ed.). Westport, CT: AVI.

Herrman, T., Reed, C., Harner, J., & Heishman, A. (1998). Emergency storage of grain: Outdoor piling (MF-2363). Manhattan, KS: Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Hoseney, R. C., & Faubion, J. M. (1992). Chapter 1: Physical properties of cereal grains. In D. B. Sauer (Ed.), *Storage of cereal grains and their products.* St. Paul, MN: American Association of Cereal Chemists.

Kalman, H., Goder, D., Rivkin, M., & Bendor, G. (1993). The effect of the particle-surface friction coefficient on the angle of repose. *Bulk Solids Handling, 13*(1), 123-128.

Kurkuri, M. D., Randall, C., & Losic, D. (2012). New method of measuring the angle of repose of hard wheat grain. *Chemeca: Quality of Life through Chemical Engineering.* Retrieved from <http://search.informit.com.au/documentSummary;dn=867689814319948;res=IELENG> EISBN: 9781922107596

Linoya, K., Gotoh, K., & Higashitani, K. (1990). Powder technology handbook. New York, NY: Marcel Dekker.

Lorenzen, R. T. (1959). Moisture effect on friction coefficients of small grain. ASAE Paper No. 59-416. St. Joseph, MI: ASAE.

Mohsenin, N. N. (1986). *Physical properties of plant and animal materials.* New York, NY: Gordon and Breach, Science Publ.

Molenda, M., & Horabik, J. (2005). Part 1: Characterization of mechanical properties of particulate solids for storage and 1216 Transactions of the ASABE handling. In J. Horabik, & J. Laskowski (Eds.), *Mechanical properties of granular agro-materials and food powders for industrial practice.* Lublin: Institute of Agrophysics Polish Academy of Sciences.

MWPS-29. (1999). Dry grain aeration systems design handbook, MWPS-29. Revised 1st. Ames, IA: Midwest Plan Service. Iowa State University.

Nelson, S. O. (2002). Dimensional and density data for seeds of cereal grain and other crops. *Trans. ASAE, 45*(1), 165-170. http://dx.doi.org/10.13031/2013.7859

Pierce, R. O., & Bodman, G. R. (1987). Piling angles of corn and milo. ASAE Paper No. 87-4058. St. Joseph, MI: ASAE.

Seifi, M. R., & Alimardani, R. (2010). The moisture content effect on some physical and mechanical properties of corn. *J. Agric. Sci., 2*(4), 125-134. http://dx.doi.org/10.5539/jas.v2n4p125

Stahl, B. M. (1950). Grain bin measurements. USDA Circular No. 835. Washington, DC: USDA.

Tabatabaeefar, A. (2003). Moisture dependent physical properties of wheat. *Int. Agrophys., 17*, 207-211.

USDA-GIPSA. (2009). Inspecting grain: Practical procedures for grain handlers. Washington, DC: USDA Grain Inspection, Packers and Stockyards Administration. Federal Grain Inspection Service. Retrieved from https://www.gipsa.usda.gov/fgis/eBooks/PracticalProcedures/Practical%20Procedures_2016-09-26.pdf