FRICTION COEFFICIENTS FOR DRIED DISTILLERS GRAINS ON EIGHT STRUCTURAL SURFACES

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ABSTRACT. *Static and dynamic coefficients of friction on structural surfaces play important roles in the power requirements and material selection for equipment used in handling and storing agricultural commodities. However, friction data on dried distillers grains with solubles (DDGS) is limited. Further, lack of a standardized method for determining friction coefficient on grain handling materials presents a challenge. This article describes studies carried out to determine the static coefficient of friction (*μ_s*) and dynamic coefficient of friction (*μ_d*) for corn DDGS at 10%, 8.2%, and 6.5% moisture content (all moistures are % wet basis) on eight structural surfaces: High-Density Polyethylene (HDPE), Ultra-High Molecular Weight Polyethylene (UHMWPE), 20-gage aluminum, galvanized steel, mild steel, 18-gage stainless steel, poplar wood, and pine wood. For all structural surfaces and DDGS moistures tested,* μ_s *lies in the range from 0.20 to 0.43 and* μ_d *in the range from 0.17 to 0.35. The* μ_s *values were higher than corresponding* μ_d *values for all moisture levels. In general,* μ_s *and* μ_d *increased linearly with increasing moisture for metal and wood surfaces. Pine wood had the highest* μ_s *at all moisture levels and the highest* μ_d *at 8.2% and 10% moisture. HDPE had the lowest* μ_s *and* μ_d *at 10% moisture followed by the values for UHMWPE. For these surfaces the* μ_s *and* μ_d *remained the same or decreased with increasing DDGS moisture. Among the metal surfaces, galvanized steel and aluminum exhibited similar coefficient of friction characteristics however galvanized steel had the lowest* μ_s *and* μ_d *at 6.5% and 8.2% moisture.*

Keywords. *DDGS, Dynamic coefficient of friction, Static coefficient of friction.*

In the United States, corn is the grain of choice for ethanol production because its dry matter is nearly two-thirds starch (Loy, 2007). In addition, the infrastructure for corn production and transportation is well developed. Corn is converted into ethanol using either the dry-grind process or the wet milling process (Singh et al., 2001; Belyea et al., 2004). In the past, ethanol was produced mainly by wet milling. However, in the last few decades dry-grind ethanol capacity has increased and now accounts for 90% of ethanol production (RFA, 2007). The dry-grind process is more energy efficient and cost effective than wet milling (Dale and Tyner, 2006). Dry-grind ethanol plants have low investment cost (Rodríguez et al., 2010), operate with a high ethanol yield, and are simple to construct because of simple processes involved (Rausch and Belyea, 2006).

The dry-grind corn ethanol production process consists of the following major steps: dry-grinding, liquefaction, saccharification, fermentation, distillation, and co-product recovery. Kernels are first ground into a meal to increase surface area and expose starch (Dale and Tyner, 2006). Then, the ground meal is slurried with water and alpha-amylase enzyme to form “mash” (Butzen and Haefele, 2008). The alpha-amylase enzyme along with yeast causes fermentation to occur (Berger and Singh, 2010) which produces carbon dioxide and ethanol (Kwiatkowski et al., 2006). Ethanol is recovered from the mash by distillation leaving the non-volatile components called whole stillage (Bothast and Schlicher, 2005) which is drawn from the distillation unit and centrifuged to produce wet distillers grains and thin stillage (Rausch and Belyea, 2006).

The thin stillage is concentrated into syrups using evaporators (Arora et al., 2011). The syrup is usually added to wet distillers grains to form wet distillers grains with solubles (WDGS) (Kaiser, 2008) with a moisture content of about 65% (all moistures are % wet basis). When WDGS is dried to between 50% and 55% moisture, it is referred to as modified wet distillers grains with solubles (MWDGS) (Perrin et al., 2009). WDGS or MWDGS is often dried to form dried distillers grains with solubles (DDGS) with moisture between 10% and 12%.

DDGS are used primarily as livestock feed because of high metabolizable energy concentrations and ruminally undegradable protein (Belyea et al., 2010). This high-value co-product is shipped all over the United States by trucks and rail cars due to increasing demand and significant quantities produced. DDGS usually becomes hardened during transportation and can damage railcars (Ganesan et al., 2008). Caking, clustering, and sticking of DDGS particles during transport and storage hinders flow and

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requires additional labor, machinery, and time, therefore increasing the cost of the DDGS and causing substantial economic loss (Rock and Shwedes, 2005; Bhadra et al., 2009). Shipping DDGS by railway cars and trucks can also be problematic during unloading (Rosentrater, 2006; Bhadra et al., 2009). Handling of DDGS has been a challenge due to issues with flowability over surfaces (Ganesan et al., 2008). One critical factor that influences efficiency and motion of surfaces in contact is friction (Yanada and Sekikawa, 2008). Friction is defined by the empirical law: $F = \mu \times N$, where F is the horizontal force required to move a material in contact with a surface, μ is the coefficient of friction, and N is the applied normal force (Kostaropoulos et al., 1997). The resistive force (friction) when a stationary object begins motion is called the static coefficient of friction (μ_s) and when the object is already in motion is called dynamic coefficient of friction (μ_d).

Physical and chemical properties of DDGS can affect the frictional behavior between surfaces. Effects of structural surfaces and moisture on friction coefficients have been reported for various agricultural products (Lawton, 1980; Kostaropoulos et al., 1997; Baryeh, 2001, 2002; Sacilik et al., 2003; Al-Mahasneh and Rababah, 2007; Coşkuner and Karababa, 2007; Subramanian and Viswanathan, 2007; Nwakonobi and Onwualu, 2009; Pradhan et al., 2009;). Also, heat generated between particles in motion caused by friction increases power requirement (Holm et al., 1985). Flow behavior of DDGS depends on characteristics such as temperature, relative humidity, and compression pressures (Ganesan et al., 2008), moisture, time of storage, fat composition, particle size and shape, compaction pressure distribution, and vibrations during transportation of particles (Bhadra et al., 2009).

To reduce frictional losses and increase efficiency, it is desirable to select materials with low friction coefficients to be in contact with DDGS during handling and storing operations. No reports of friction coefficients of DDGS on various structural materials was found in the literature, therefore this research was undertaken to determine static and dynamic friction coefficients for DDGS at 10%, 8.2%, and 6.5% moisture. This study provides an understanding and new information on the flowability behavior of DDGS on eight structural surfaces.

MATERIALS AND METHODS

About 10 kg of DDGS was obtained from the Lincolnway Energy ethanol plant west of Nevada, Iowa, on 25 March 2010, sealed in a large plastic tub and transported back to Iowa State University for testing. The DDGS sample was divided into three equal subsamples. One subsample was subjected to tests immediately, whereas the other two were allowed to dry in ambient air to attain lower moisture contents.

Moisture content was determined following ASAE Standard Method 352.2 (*ASABE Standards*, 2008b) using a forced-convection laboratory oven at 103°C for 72 h. The initial DDGS moisture content was 10%. After allowing the DDGS to dry in ambient air, moisture contents of subsamples dropped to 8.2% and 6.5%, respectively.

Particle size was determined following ANSI/ASAE Standard Method S319.3 (*ASABE Standards*, 2008a) by sieving to express the fineness of the DDGS. Three independent experiments conducted in triplicate were performed. The average geometric mean diameter (dgw) of DDGS particles was found to be 0.397 mm with a geometric standard deviation (S_{gw}) of 0.119 mm. Particle size distribution is shown in figure 1. Particle size is a key factor that influences flowability. Fitzpatrick et al. (2004) observed that reducing particle size tends to reduce flowability because the particle surface area per unit mass increases as particle size decreases, providing a greater surface area for surface cohesive forces to interact.

Friction coefficients for DDGS were determined as a function of DDGS pressure by sliding test strips through

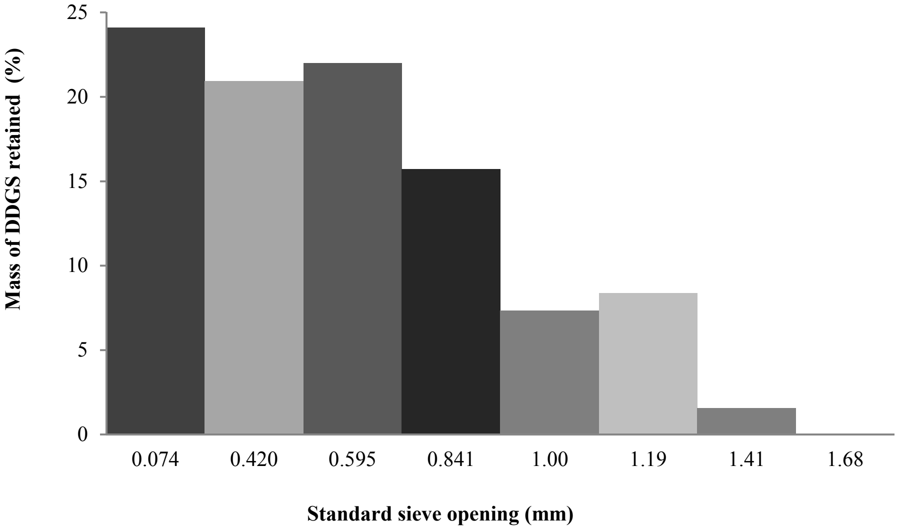

Figure 1. Particle size distribution of experimental dried distillers grains with solubles (DDGS).

beds of DDGS. This approach of friction coefficient determination was used in previous studies (Buelow, 1961; Brubakar and Pos, 1965; Snyder et al., 1967; Nwakonobi and Onwualu, 2009). The experimental setup was used originally by Ross et al. (1987) and is shown in figure 2. Sliding speed has been reported to affect coefficient of friction (Ross et al., 1987; Molenda et al., 2000). All experiments were conducted using sliding speed of 120 mm/min. A normal pressure of 1.6 kPa was applied on the pressure plate using four weights (W_1, W_2, W_3, W_4) as illustrated in figure 2. The same pressure was used throughout the experiment. Friction coefficient values and graphs were automatically generated for each test strip by Sintech TestWorks® computer software (MTS System Corporation, Research Triangle Park, N.C.).

A material testing workstation Model 65/D (MTS System Corporation, Research Triangle Park, N.C.) was used following the method of Ross et al. (1987). The workstation consists of a load cell, tensile testing hardware controlled by Sintech TestWorks® computer software. The MTS® machine was calibrated using a 22.7-kg (50-lb) load cell.

The test apparatus is made of oak wood (fig. 2) and is designed so that 75- × 635-mm test strips can be pulled through a bed of DDGS without contacting the wood frame. A detailed apparatus description can be found in Ross et al. (1987). The bottom frame was first overfilled with DDGS and screeded level with the top of the frame. Test strips of eight structural materials with dimensions 75 × 635 mm and various thicknesses were, in turn, gently placed on top of the DDGS bed through the slot on the middle and bottom frame. Table 1 lists all test strip materials (HDPE stands for high-density polyethylene and UHMWPE stands for ultra-high molecular weight polyethylene). Then the middle frame was placed over the test strip, loaded with DDGS and screeded level with the top of the frame. The top frame was placed on top of the middle frame and fastened using four bolts and wing nuts.

An s-hook was connected to a cable linked to the test strips. The cable extended around a pulley and connected to the vertically-mounted load cell as shown in figure 2. The pulley allowed the test machine to operate vertically, while sliding the test strip through the DDGS horizontally. There was no evidence of bending of the test strips during the experiment. The load cell measured the force F_1 required to pull the test strip through the DDGS and the MTS's Sintech TestWorks® software automatically generated and recorded μ_s and μ_d values. All experiments were conducted in triplicate. Test strips were wiped clean and unused DDGS from the same batch was used for each test strip and repetition.

STATISTICAL ANALYSIS

Statistical analysis of data was carried out using the SAS 9.4 Program (SAS Institute Inc., Cary, N.C.). All results were expressed as means ± SE and statistical significance between the groups was assessed by using analysis of variance (ANOVA) and Duncan's multiple range test. The level of significance used was $p<0.05$.

RESULTS AND DISCUSSION

Static and dynamic friction coefficients for DDGS at three different moistures (10%, 8.2%, and 6.5%) on various structural surfaces were determined. A sample graph generated from TestWorks® software is shown in figure 3.

The X-axis represents the displacement of test strips and the Y-axis represents the load in kg. Note that total movement of the test strip is about 5 mm. The three data points on the graph show (from left) the initial load detected by the load cell, the load and extension at which μ_s

Table 1. Physical properties of structural materials tested for friction.

Property	HDPE	UHMWPE	Aluminum (20 gage)	Galvanized Steel	Stainless Steel (18 gage)	Mild Steel	Poplar Wood	Pine Wood
Color	White-opaque	Black	Silvery-white	Silvery-gray	Silver	Black	Pale yellow	Light reddish brown
Thickness, mm (in.)	3.3 (0.13)	4.8 (0.19)	0.91 (0.036)	0.76 (0.030)	1.2 (0.047)	1.4 (0.055)	6.1 (0.24)	9.6 (0.38)
Surface properties	Smooth, slightly waxy to touch (Peacock, 2000)	Smooth, slippery (Acton, 2013)	Smooth surface finish as tested	Smooth surface finish as tested	Smooth surface finish as tested	Smooth surface finish as tested	Planed, tested parallel to grain	Planed, tested parallel to grain
Density, g/cm^3	0.94-0.97 (Peacock, 2000)	0.93-0.935 (Doran and Cather, 2014)	2.7 (Davis, 1993)		7.75-8.05 (Haynes, 2014)		0.3-0.39 (Dickmann et al., 2001)	0.35-0.5 (Gregory et al., 2009)

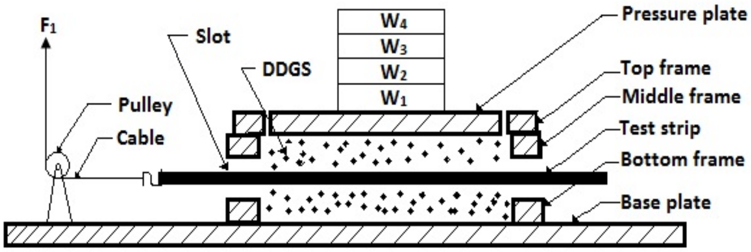

Figure 2. A cross-section of the experimental setup used to determine friction coefficient of DDGS on the various surfaces (Ross et al., 1987).

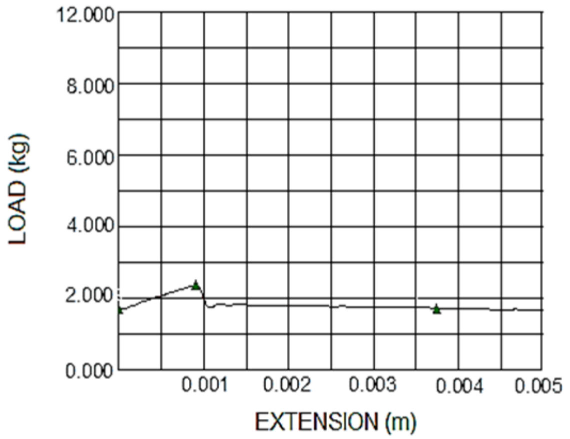

Figure 3. A sample TestWorks® plot showing the force required to pull galvanized steel through a bed of DDGS at 8.2% moisture.

was calculated, and finally the load and extension at which μ_d was calculated.

The μ_s and μ_d between DDGS and the eight structural surfaces at the three moisture levels are listed in table 2. All measurements were made in triplicate and average results are reported along with standard deviations. Coefficients of variation (%) for μ_s and μ_d values are presented in table 3.

The results of these tests show that moisture and structural surface have significant effects on DDGS μ_s and μ_d ($p < 0.001$). Interaction effects of the experimental factors on friction coefficients were highly significant ($p < 0.001$). In general, a linear correlation was observed between friction coefficients and moisture content. Both μ_s and μ_d increased linearly with increasing moisture for the metal and wood surfaces tested. Similar results have been observed in previous studies (Lawton, 1980; Baryeh, 2001, 2002; Al-Mahasneh and Rababah, 2007; Coşkuner and Karababa, 2007; Subramanian and Viswanathan, 2007; Nwakonobi and Onwualu, 2009; Pradhan et al., 2009). Previous studies have shown that increased friction coefficient with increasing moisture content may be due to increasing cohesive and adhesive forces acting on the surface of contact, the nature of structural surface, and inter-particulate properties (Mohsenin, 1980; Kostaropoulos et al., 1997; Pradhan et al., 2009).

In contrast, μ_s and μ_d values for the plastics (HDPE and UHMWPE) did not increase with increasing moisture. This phenomenon could be due to the nature of the plastics smooth molecular profiles (Pooley and Tabor, 1972). Interestingly, the μ_d for UHMWPE remained constant for all moistures. However, values for μ_s for both plastics and μ_d for HDPE decreased with increasing DDGS moisture. During our study, it was observed that DDGS at 6.5% and 8.5% moisture was strongly attracted to the plastics at close contact. As a result, the plastics gave high μ_s and μ_d at these moisture levels. This could be due to higher forces of adhesion of the drier DDGS to the plastic surfaces. Lawton (1980), working with cereal grains and seven different materials, observed higher coefficients of adhesion in drier samples.

Table 3. Coefficients of variation (%) for static and dynamic friction coefficients in table 2.

DDGS Moisture (%)	10		8.2		6.5	
Structural Surface	μ_s	μ_d	μ_s	μ_d	μ_s	μ_d
HDPE	11.9	11.9	2.5	2.5	10.8	10.8
UHMWPE	7.3	7.3	8.5	8.5	9.3	9.3
Aluminum	8.9	8.9	3.3	3.3	5.5	5.5
Galvanized steel	10.3	10.3	3.2	3.2	8.1	8.1
Stainless steel	2.8	2.8	8.5	8.5	5.7	5.7
Mild steel	4.2	4.2	5.5	5.5	1.8	1.8
Poplar wood	1.6	1.6	4.1	4.1	4.5	4.5
Pine wood	3.2	3.2	5.2	5.2	7.2	7.2

Of the eight material surfaces tested, it was found that μ_s values were greater than their corresponding μ_d for all moistures. Pine wood exhibited the highest μ_s and μ_d at all moistures. Similar behavior for wood surfaces was observed by Baryeh (2001) and (Coşkuner and Karababa, 2007). The μ_s characteristic of the surfaces at 10% DDGS moisture follows in an increasing order: HDPE (0.20), UHMWPE (0.25), aluminum (0.30), galvanized steel (0.30), poplar (0.34), stainless steel (0.35), mild steel (0.41), and pine (0.43). At 8.2% moisture, galvanized steel (0.25) had the lowest μ_s followed by aluminum (0.26), HDPE (0.27), UHMWPE (0.28), stainless steel (0.31), poplar (0.34), mild steel (0.36), and pine (0.40). Similarly, galvanized steel (0.22) had the lowest μ_s at 6.5% moisture followed by aluminum (0.24), HDPE (0.25), stainless steel (0.28), UHMWPE (0.28), mild steel (0.29), poplar (0.31), and pine (0.32).

The increasing order of the structural surfaces for μ_d values was not the same as μ_s values, but generally HDPE (0.17) had the lowest μ_d at 10% DDGS moisture followed by UHMWPE (0.21), aluminum (0.23), galvanized steel (0.24), poplar (0.25), stainless steel (0.28), mild steel (0.31), and pine (0.35). At 8.2% moisture galvanized steel (0.19) exhibited the lowest μ_d followed by aluminum (0.21), UHMWPE (0.22), HDPE (0.23), stainless steel (0.26), mild steel (0.26), poplar (0.26), and pine (0.35). At 6.5% DDGS moisture, galvanized steel (0.17) had the lowest μ_d followed by aluminum (0.18), HDPE (0.21),

Table 2. Static coefficients of friction (μ_s) and dynamic coefficients of friction (μ_d) of DDGS on eight structural surfaces.

DDGS Moisture (%)	10[a]		8.2		6.5	
Structural Surface	μ_s	μ_d	μ_s	μ_d	μ_s	μ_d
HDPE	0.20 ± 0.02^{e}	0.17 ± 0.02^{f}	0.27 ± 0.01^{ef}	0.23 ± 0.01^{c}	0.25 ± 0.03^{b}	0.21 ± 0.03^{abc}
UHMWPE	0.25 ± 0.02^{d}	0.21 ± 0.02^{e}	0.28 ± 0.02^{de}	0.22 ± 0.02^{cd}	0.28 ± 0.03^{a}	0.21 ± 0.03^{abc}
Aluminum	0.30 ± 0.03^{c}	0.23 ± 0.03^{de}	0.26 ± 0.01^{ef}	0.21 ± 0.01^{cd}	0.24 ± 0.01^{b}	0.18 ± 0.01^{bc}
Galvanized steel	0.30 ± 0.03^{c}	0.24 ± 0.03^{de}	0.25 ± 0.01^{f}	0.19 ± 0.01^{d}	0.22 ± 0.02^{b}	0.17 ± 0.02^{c}
Stainless steel	0.35 ± 0.01^{b}	0.28 ± 0.01^{bc}	0.31 ± 0.03^{cd}	0.26 ± 0.03^{b}	0.28 ± 0.02^{a}	0.22 ± 0.02^{ab}
Mild steel	0.41 ± 0.02^{a}	0.31 ± 0.02^{ab}	0.36 ± 0.02^{b}	0.26 ± 0.02^{b}	0.29 ± 0.01^{a}	0.21 ± 0.01^{abc}
Poplar wood	0.34 ± 0.01^{b}	0.25 ± 0.01^{cd}	0.34 ± 0.01^{bc}	0.26 ± 0.01^{b}	0.31 ± 0.01^{a}	0.24 ± 0.01^{a}
Pine wood	0.43 ± 0.01^{a}	0.35 ± 0.01^{a}	0.40 ± 0.02^{a}	0.35 ± 0.02^{a}	0.32 ± 0.02^{a}	0.24 ± 0.02^{a}

[a] Values are means ±SD. Means in each column sharing the same superscript letter are not significantly different at $p<0.05$ by Duncan's multiple range test.

UHMWPE (0.21), mild steel (0.21), stainless steel (0.22), poplar (0.24), and pine (0.24).

It can be seen from the results that galvanized steel and aluminum were found to have the lowest μ_s and μ_d at all moisture levels for the metal surfaces. Sacilik et al. (2003), working on galvanized metal and hemp seeds, had similar observations for a moisture range from 8.62% to 20.88%. Mild steel had the highest μ_s among the metal surfaces. Subramanian and Viswanathan (2007) found that mild steel offers the greatest μ_s when tested against galvanized steel, aluminum, and stainless steel on millet grains.

Linear relationships between μ_s, μ_d, and DDGS moisture for the eight structural surfaces are presented in tables 4 and 5 respectively. Coefficients of determination (R^2) range from 0.62 to 1.00 and 0.24 to 1.00 for μ_s and μ_d, respectively, and DDGS moisture. However, the accuracy of HDPE and poplar wood μ_d could be questioned as the coefficients of determination are below 0.5. No applicable linear relationship between μ_d and DDGS moisture for UHMWPE was found because it was the only case tested in which μ_d remained constant at 0.21 for all DDGS moisture levels. The applicability of the equations listed in table 4 and table 5 are limited to the DDGS moisture range tested (6.5% to 10%).

The μ_s for all structural surfaces and DDGS moisture lies in the range from 0.20 to 0.43 and μ_d in the range from 0.17 to 0.35. The ratios of the corresponding μ_s for each surface at the moisture levels remained almost constant (standard deviations ≤ 0.15) likewise those of μ_d (standard deviations ≤ 0.16).

The friction and other physical properties of grains are crucial in the design of storage, processing, and material handling equipment. It is acknowledged that friction coefficient could vary depending on the experimental technique of grain friction determination and the properties of the grain samples (Lawton, 1980). Therefore, it is important to use these results comparatively rather than precisely due to variations in DDGS handling, construction materials, physical characteristics of DDGS, and the method of friction coefficient determination. Accordingly, there is the need to develop a standard method for determining friction coefficient to eliminate inconsistencies of results.

Table 4. Relationship between static friction coefficient (μ_s) and DDGS moisture content (M) for eight structural surfaces.

Structural Surface	Equation	Coefficient of Determination, R^2
HDPE	$\mu_s = -0.015M + 0.356$	0.62
UHMWP	$\mu_s = -0.01M + 0.341$	0.76
Aluminum	$\mu_s = 0.020M + 0.099$	1.00
Galvanized steel	$\mu_s = 0.023M + 0.068$	0.98
Stainless steel	$\mu_s = 0.020M + 0.149$	1.00
Mild steel	$\mu_s = 0.034M + 0.068$	1.00
Poplar wood	$\mu_s = 0.10M + 0.256$	0.96
Pine wood	$\mu_s = 0.031M + 0.126$	0.93

Table 5. Relationship between dynamic friction coefficient (μ_d) and DDGS moisture content (M) for eight structural surfaces.

Structural Surface	Equation	Coefficient of Determination, R^2
HDPE	$\mu_d = -0.012M + 0.300$	0.44
UHMWPE	$\mu_d = 0.21$	-
Aluminum	$\mu_d = 0.014M + 0.090$	0.98
Galvanized steel	$\mu_d = 0.020M + 0.035$	0.95
Stainless steel	$\mu_d = 0.017M + 0.113$	0.96
Mild steel	$\mu_d = 0.029M + 0.025$	1.00
Poplar wood	$\mu_d = 0.003M + 0.227$	0.24
Pine wood	$\mu_d = 0.031M + 0.057$	0.74

CONCLUSIONS

Based on this study, the following conclusions were drawn from DDGS friction coefficients on eight structural surfaces:

1. Structural surfaces and DDGS moisture both had significant effects on static and dynamic coefficients of friction. Interactions were also significant.
2. Static friction coefficients were higher than dynamic coefficients for all moistures and structural surfaces, and both static and dynamic coefficients increased linearly with DDGS moisture for all metals and woods, but not for plastics.
3. Galvanized steel and aluminum exhibited the lowest static and dynamic friction coefficients among metals.

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