Journal of Advanced Research 8 (2017) 351–361

Contents lists available at ScienceDirect

Journal of Advanced Research

journal homepage: www.elsevier.com/locate/jare

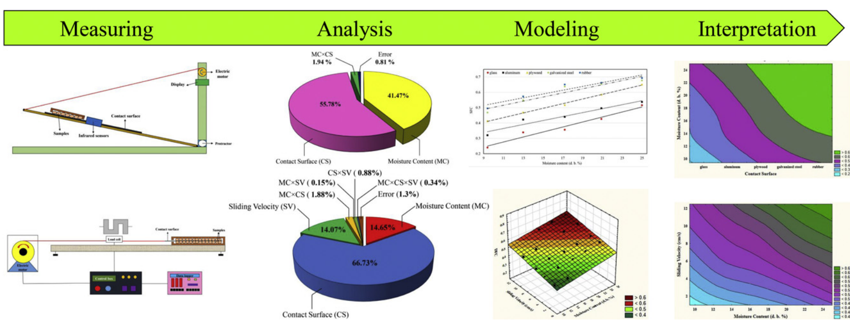
Original Article

A comprehensive investigation on static and dynamic friction coefficients of wheat grain with the adoption of statistical analysis

S.M. Shafaei, S. Kamgar *

Department of Biosystems Engineering, School of Agriculture, Shiraz University, Shiraz 71441-65186, Iran

G R A P H I C A L   A B S T R A C T



A R T I C L E   I N F O

Article history:
Received 6 February 2017
Revised 16 April 2017
Accepted 16 April 2017
Available online 19 April 2017

Keywords:
Analysis of variance
Duncan's multiple range test
Moisture content
Sliding velocity
Contact surface

A B S T R A C T

This paper deals with studying and modeling static friction coefficient (SFC) and dynamic friction coefficient (DFC) of wheat grain as affected by several treatments. Significance of single effect (SE) and dual interaction effect (DIE) of treatments (moisture content and contact surface) on SFC and, SE, DIE, and triple interaction effect (TIE) of treatments (moisture content, contact surface and sliding velocity) on DFC were determined using statistical analysis methods. Multiple linear regression (MLR) modeling was employed to predict SFC and DFC on different contact surfaces. Predictive ability of developed MLR models was evaluated using some statistical parameters (coefficient of determination (R^2), root mean square error (RMSE), and mean relative deviation modulus (MRDM)). Results indicated that significant increasing DIE of treatments on SFC was 3.2 and 3 times greater than significant increasing SE of moisture content and contact surface, respectively. In case of DFC, the significant increasing TIE of treatments was 8.8, 3.7, and 8.9 times greater than SE of moisture content, contact surface, and sliding velocity, respectively. It was also found that the SE of contact surface on SFC was 1.1 times greater than that of moisture content and the SE of contact surface on DFC was 2.4 times greater than that of moisture content or sliding velocity. According to the reasonable average of statistical parameters ($R^2 = 0.955$, RMSE = 0.01788 and MRDM = 3.152%), the SFC and DFC could be successfully predicted by suggested MLR models. Practically, it is recommended to apply the models for direct prediction of SFC and DFC, respective to each contact surface, based on moisture content and sliding velocity.

Abbreviations: 2DC, two-dimensional chart; 3DC, three-dimensional chart; ANOVA, analysis of variance; DFC, dynamic friction coefficient; DIE, dual interaction effect; DMRT, Duncan's multiple range test; GMD, geometric mean diameter; MRDM, mean relative deviation modulus; MLR, multiple linear regression; RMSE, root mean square error; SFC, static friction coefficient; SE, single effect; TIE, triple interaction effect; MAVET, mean of absolute values of error term.

Peer review under responsibility of Cairo University.

* Corresponding author.
E-mail address: kamgar@shirazu.ac.ir (S. Kamgar).

http://dx.doi.org/10.1016/j.jare.2017.04.003
2090-1232/

Nomenclature

FF	friction force (N)	NF	normal force (N)
FC	friction coefficient	SSv	sum of square of variation
S	sphericity (%)	FC_{min}	minimum friction coefficient
W	width (mm)	SS_t	total sum of square
W_w	mass of added distilled water (g)	SD	standard deviation
W_t	initial mass of sample (g)	$FC_{act,i}$	ith actual friction coefficient
x_1	1st MLR model variable	$FC_{pre,i}$	ith predicted friction coefficient
x_2	2nd MLR model variable	N	number of data
x_n	nth MLR model variable	a_n	nth MLR model coefficient
ε	error term of MLR model	a_2	2nd MLR model coefficient
FC_{actave}	average of actual friction coefficient	a_1	1st MLR model coefficient
M_f	final moisture content of sample (d. b.%)	a_0	MLR model constant
M_i	initial moisture content of sample (d. b.%)	S_a	surface area (mm^2)
M	mean of used data	T	thickness (mm)
CV	coefficient of variation (%)	L	length (mm)
FC_{max}	maximum friction coefficient	D_g	GMD (mm)
C	contribution of variation (%)	RMSE	root mean square error
CNU	coefficient of non-uniformity (%)	MRDM	mean relative deviation modulus (%)

Introduction

Wheat is a dominate major crop in human food. The crop is widely cultivated throughout the world. Hence, investigation of different aspects of wheat in planting, harvesting, transporting, storing and processing stage is of great importance in management of its production and preservation.

Physical properties of agricultural products are frequently used for designing of agricultural machinery and equipment of related post-harvest industries [1]. Some physical properties are major dimensions (length, width and thickness), mass, GMD, sphericity and friction coefficients.

Friction coefficients of crops vary on different contact surfaces. Therefore, exact determination of friction coefficients of the crop on different contact surfaces can be useful in performance optimization of mechanical equipment (conveyors, separation, cleaning, drying and storing tools), and consequently, reduction and increment of harmful damages and economic efficiency, respectively [2].

Friction forces perform between two contact surfaces. Required force for initial movement of a motionless object depends on static friction force and the force for continuous movement of an object at a specific velocity relies on dynamic friction force. According to Brubaker and Pos [3], the relation between friction force and friction coefficient can be presented as following equation.

$$FF = FC \times NF \tag{1}$$

According to Eq. (1), friction coefficient directly affects the friction force value. Therefore, researches about the effect of various conditions and treatments on friction coefficients are needed to gain information for controlling friction forces.

Friction coefficients include SFC and DFC with respect to static and dynamic friction forces, respectively. The SFC and DFC of crop depend on moisture content. Additionally, in case of DFC, the sliding velocity is also an important factor [2].

The frictional forces occur on a vertical plane in storage structures and handling equipment of wheat grain. On walls and floor of storage bins, frictional forces play an important role in discharging process in the plug flow region. The SFC and DFC, and consequently frictional forces, are influenced by the interaction of wheat grain particles and the surface of bin wall [4]. This interaction significantly affects the distribution and magnitude of loads applied on storage structures [5]. However, knowledge about the impact of many treatments on the SFC and DFC is still incomplete. Thus, additional experimental works are needed to determine the exact frictional behavior of wheat grain on different contact surfaces.

A review of published works confirmed that although the SFC of wheat grain has been studied by several previous investigators [3–23], there is no extended study for the determination of the effect of moisture content and contact surface on SFC of wheat grain. Neither, there are perfect attempts available in literature reporting the effect of moisture content, contact surface or sliding velocity on DFC of wheat grain [24–30]. Therefore, a comprehensive investigation of SFC and DFC for wheat grain taking several experimental conditions into considerations will be useful for optimization of storage and processing structures, especially grain bins.

In light of the above mentioned deficiencies and the benefits of knowing about SFC and DFC of wheat grain for optimization of related industry structures and equipment, the key scope of the present work on wheat grain was concentrated on following items:

(1) Precise determination of SFC and DFC as effected by moisture content and contact surface, and moisture content, contact surface and sliding velocity, respectively.
(2) To carry out statistical analysis to study the effect of moisture content, sliding velocity, contact surface and their DIE and TIE on DFC, and moisture content, contact surface and their DIE on SFC.
(3) Comparing statistical significance of the effect of different treatment levels on SFC and DFC.
(4) Assessment of predictive ability of MLR model for SFC and DFC based on multiple input variables (moisture content and sliding velocity) for each contact surface.

Material and methods

Grain collection

Shiroudi variety of wheat (*Triticum* aestivum L.), one of the most commonly used varieties in south region of Iran, was collected from Seed and Plant Breeding Unit, Agricultural Research Center of Fars province. Initially, the grains were cleaned by hand in order to remove undesired materials such as gravel, stone and injured