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Statistical analysis of experimental condition effects on free abrasive wear of UHMWPE

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Friction and wear of the ultra-high molecular weight polyethylene (UHMWPE) were extensively investigated as it has many excellent properties. For example, UHMWPE was used for parts of equipment used in chemical engineering, textile engineering, food processing, paper making industry, pharmacy, transportation engineering, agricultural engineering, coal and ceramic production. UHMWPE was substituted for carbon steel, stainless steel, and bronze, because of its better anti-chemical-corrosion, water-repellent function, anti-adhesion, self-lubrication, and higher impact resistance [1]. The dry sliding friction coefficient of UHMWPE is lower than that of other polymers, except polytetrafluoroethylene. The wear resistance of UHMWPE is much higher than that of carbon steel and bronze in sliding friction, and than that of nylon-66, teflon, carbon steel, ceramic, and enamel coating under such abrasive wear conditions as soil and water–sand slurry [1–3].

The abrasive wear of soil engaging components of agricultural machines against soil is a free-abrasive wear. The free abrasive wear phenomena also occur in working parts of such equipment as water power equipment, the transportation pipe lines in coal production and transportation, concrete production and transportation equipment, and food production and transportation equipment. The adhesion and friction of soil engaging components against soil are also important properties. It was shown that UHMWPE had better anti-adhesion and anti-friction ability against soil than steel, ceramic, enamel, and other polymers except polytetrafluoroethylene (teflon) [2]. The statistical analysis of the free abrasive wear of UHMWPE was performed in order to examine the effects of the abrasive particle size and the relative sliding velocity.

Powdered UHMWPE of a molecular weight of 2.5×10^6 was used. The preparation procedure of the test specimens was: the UHMWPE powder was filled into a mold and pressed into the test specimens on a hydraulic press under 100 MPa which were then sintered in a stove at 190 °C, followed by hot-pressing under 20 MPa. The test specimens had dimensions 60 mm × 35 mm × 6 mm.

Three different grades of quartz sand (0.420–0.840, 0.214–0.420, and 0.104–0.214 mm, respectively) and bentonite (76 μm) were used as the abrasive material, containing quartz sand of 96.5 wt% and bentonite of 3.5 wt%. In addition, the abrasive material had a water content of 3–5 wt%.

The free abrasive wear tests were run on a rotary-disc-type abrasive wear tester as shown in Fig. 1. Four specimens can be installed on the specimen holder at positions perpendicular to each other. Their position can be changed successively to abrade one by one every 803.4 m of sliding distance. The abrading specimen was embedded 40 mm in the abrasive. The impact angle of abrasive against the abrading surface of the test specimen was 35°. The rotary disc rotated to drive the abrasive to slide against the abrading specimen during abrasive tests. The total sliding distance for each specimen was 25708.8 m. The relative sliding velocity was 1.68, 2.35, and 3.02 m/s, respectively. The temperature of the surrounding air was 20 °C. The three compacting wheels were kept in fixed positions in order to maintain a constant bulk density of the abrasive material for all abrasive wear tests. The abrasive wear of specimens was expressed by their abrasion volume. The microscopic morphologies of the abraded surfaces were analyzed by scanning electron microscopy (SEM).

The experimental data of the abrasive wear reflected some relation of the experimental index with the experimental factors although the experimental data were obtained through several independent experiments. The statistical relation can be found through experimental optimal design methods, particularly the interaction between two or more factors with the experimental index. The regression analysis of the free abrasive wear property of the UHMWPE was performed by an orthogonal polynomial in order to examine the effects of the abrasive particle size and the relative sliding velocity as the experimental conditions on the abrasive wear property. Each conditional factor had three levels with the same interval between two adjacent levels. The three-level values of the abrasive particle size (z_1) were 0.480, 0.315, and 0.150 mm, respectively, and the interval was $\Delta z_1 = 0.165$. The three-level values of the sliding velocity (z_2) were 1.68, 2.35, and 3.02 m/s, respectively, and the interval was $\Delta z_2 = 1.67$.

In regression design, the Fisher's recursive formulas are usually used for constructing orthogonal polynomials, $X_j(z) = \lambda_j \varphi_j(z)$, where λ_j is a coefficient for integralization [4]. $\varphi_j(z)$ $(j = 0, 1, 2, \ldots)$ had the

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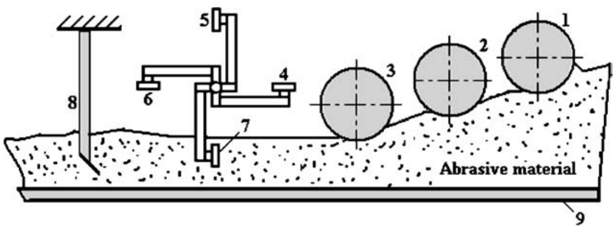

Figure 1 Schematic diagram of the operation of a rotary-disk-type abrasive wear tester. 1–3: compacting wheels; 4–7: test specimens; 8: subsoiler; 9: rotary disc.

following forms (here, the expressions are only given for $j = 0, 1, 2$):

$$\varphi_0(z) = 1$$

$$\varphi_1(z) = \frac{z - \bar{z}}{\Delta}$$

$$\varphi_2(z) = \left(\frac{z - \bar{z}}{\Delta}\right)^2 - \frac{N^2 - 1}{12}.$$

Table I lists the experimental scheme [4] for the regression analysis and the experimental results of the free abrasive wear property of UHMWPE, where

$$D_j = \sum_{i=1}^{N} [\lambda_j \varphi_j(z_i)]^2;$$

$$B_j = \sum_{i=1}^{N} [\lambda_j \varphi_j(z_j)] y_i;$$

b_j was regression coefficient, $b_j = B_j / D_j$;

$$S_j = b_j B_j;$$

$$F_j = \frac{S_j / f_j}{S_e / f_e};$$

a_j was the selected level of the significance;
y was the abrasive wear index (abrasion volume).

The regression equation of the experimental index $\hat{y}$ (abrasion volume of UHMWPE) with z_1 (abrasive particle size), z_2 (sliding velocity), and their interacting terms were expressed by the following polynomial:

$$\begin{aligned}\hat{y} = {} & b_0 + b_{11} X_1(z_1) + b_{21} X_2(z_1) + b_{12} X_1(z_2) \\ & + b_{22} X_2(z_2) + b_{12}^{(11)} X_1(z_1) X_1(z_2) \\ & + b_{12}^{(12)} X_1(z_1) X_2(z_2) + b_{12}^{(21)} X_2(z_1) X_1(z_2) \\ & + b_{12}^{(22)} X_2(z_1) X_2(z_2) \qquad (1)\end{aligned}$$

where

$$X_1(z_1) = \varphi_1(z_1) = \frac{z_1 - \bar{z}_1}{\Delta_1} = \frac{z_1 - 0.315}{0.165}$$

$$X_2(z_1) = 3\varphi_2(z_1) = 3\left[\left(\frac{z_1 - \bar{z}_1}{\Delta_1}\right)^2 - \frac{N^2 - 1}{12}\right] = \frac{3}{0.165^2}(z_1 - 0.315)^2 - 2$$

$$X_1(z_2) = \varphi_1(z_2) = \frac{z_2 - \bar{z}_2}{\Delta_2} = \frac{z_2 - 2.35}{0.67}$$

$$X_2(z_2) = 3\varphi_2(z_2) = 3\left[\left(\frac{z_2 - \bar{z}_2}{\Delta_2}\right)^2 - \frac{N^2 - 1}{12}\right] = 6.683(z_2 - 2.35)^2 - 2.$$

By putting the regression coefficients b_j in Table I into Equation 1, a regression equation expressing the relationship of the abrasion volume of the UHMWPE with the experimental factors can be obtained as follows (Equation 2):

$$\begin{aligned}\hat{y} = {} & 79.69 - 28.87 X_1(z_1) + 3.44 X_2(z_1) \\ & + 16.8 X_1(z_2) - 3.675 X_1(z_1) X_1(z_2) \\ & + 1.04 X_1(z_1) X_2(z_2) - 0.817 X_2(z_1) X_2(z_2). \qquad (2)\end{aligned}$$

The experimental errors were estimated. The sum of the error square of the experimental indexes S_e and its

TABLE I Experimental scheme and results of the abrasive wear of the UHMWPE

No.	Z_1 (mm)	Z_2 (m/s)	(1) φ_0	(2) $X_1(z_1)$	(3) $X_2(z_1)$	(4) $X_1(z_2)$	(5) $X_2(z_2)$	(6) $X_1(z_1)X_1(z_2)$	(7) $X_1(z_1)X_2(z_2)$	(8) $X_2(z_1)X_1(z_2)$	(9) $X_2(z_1)X_2(z_2)$	y $(mm)^3$
1	0.480	1.68	1	−1	1	−1	1	1	−1	−1	1	90.3
2	0.480	2.35	1	−1	1	0	−2	0	2	0	−2	115.5
3	0.480	3.02	1	−1	1	1	1	−1	−1	1	1	130.2
4	0.315	1.68	1	0	−2	−1	1	0	0	2	−2	56.7
5	0.315	2.35	1	0	−2	0	−2	0	0	0	1	69.3
6	0.315	3.02	1	0	−2	1	1	0	0	−2	−2	92.4
7	0.150	1.68	1	1	1	−1	1	−1	1	−1	1	42.0
8	0.150	2.35	1	1	1	0	−2	0	−2	0	−2	53.6
9	0.150	3.02	1	1	1	1	1	1	1	1	1	67.2
D_j			9	6	18	6	18	4	12	12	36	
B_j			717.22	−173.2	61.96	100.8	1.96	−14.7	12.5	−6.3	−29.42	
b_j			79.69	−28.87	3.44	16.8	0.109	−3.675	1.04	−0.525	−0.817	
S_j				5000.28	213.14	1693.44	0.214	54.02	13	3.31	24.04	
F_t				2500.14	106.57	846.72	0.107	27.01	6.5	1.655	12.02	
a_j				0.01	0.01	0.01	0.25	0.01	0.10	0.25	0.05	

degree of freedom f_e were

$$S_e = \sum_{i_0=1}^{4} y_{i0}^2 - \frac{1}{4}\left(\sum_{i_0=1}^{4} y_{i0}\right)^2 = 6$$
$$f_e = 4 - 1 = 3.$$

The regression coefficients were calculated and their significance was tested by F-test method in mathematical statistics and the results are also listed in Table I. After eliminating some terms that were not significant, the sum of the regression square S_{Re} and its degree of freedom f_{Re} were

$$S_{Re} = S_2 + S_3 + S_4 + S_6 + S_7 + S_9 = 6996.92$$
$$f_{Re} = 6.$$

The sum of the total error square S and its degree of freedom f were

$$S = \sum_{i=1}^{9} y_i^2 - \frac{1}{9}\left(\sum_{i=1}^{9} y_i\right)^2 = 7001.3$$
$$f = 9 - 1 = 8.$$

Let

$$S_R = S - S_{Re} = 7001.3 - 6997.92 = 3.38$$
$$f_R = f - f_{Re} = 8 - 6 = 2,$$

then the F-test result for the testing for the regression significance of Equation 2 was

$$F_{Re} = \frac{S_{Re}/f_{Re}}{S_R/f_R} = 690.13 > F_{0.01}(6,2) = 99.33.$$

In order to conduct the test for the lack of fit on Equation 2, four repeating experiments were conducted for the specimen order 5 and the experimental results are listed in Table II. The average value of the abraded volume from the repeating experiments was $\bar{y} = 69.825$. From Equation 2, $\hat{y}$ corresponding to the abrasive particle size $z_1 = 0.315$ mm and the sliding velocity $z_2 = 2.35$ m/s was $\hat{y}_0 = 69.542$. So, the F-test result for testing for the lack of fit on Equation 2 was

$$F_{lf} = \frac{(\hat{y}_0 - \bar{y})^2}{S_e/f_e} = \frac{(69.542 - 69.825)^2}{0.6/3} = 0.4 < 1$$

TABLE II The repeating experimental results of the abrasion volume of the specimen order 5

Specimen no.	Z_1 (mm)	Z_2 (m/s)	y (mm^3)
1	0.315	2.35	71.6
2	0.315	2.35	68.3
3	0.315	2.35	70.2
4	0.315	2.35	69.2

The formula F_{Re} indicates that Equation 2 had a confidence of 99% and F_{lf} suggests that Equation 2 was satisfactory.

By putting $X_1(z_1)$, $X_2(z_1)$, $X_1(z_2)$, and $X_2(z_1)$ into Equation 2 a regression equation about the abrasion volume of the UHMWPE was obtained as follows (Equation 3).

$$\begin{aligned}\hat{y} = &-164.49 + 1617.83z_1 + 181.5z_2\\ &- 1550.27z_1z_2 - 35.51z_2^2 + 336.92z_1z_2^2\\ &+ 2827.77z_1z_2^2 - 601.65z_1^2z_2.\end{aligned} \tag{3}$$

The coefficients of regression in Equation 3 indicate the effect of experimental factors (that is, abrasive particle size and sliding velocity in the present work) on the experimental index (that is, the abraded volume in the present work). According to the magnitude of the coefficients of regression in Equation 3, it is found that the effect of the abrasive particle size on the abrasion of the UHMWPE was higher than the effect of the sliding velocity. It can be also be seen from Equation 3 that there existed, to some extent, interactions between the sliding velocity and the abrasive particle size.

It was shown by scanning electron microscopy that the free abrasive wear of UHMWPE was due to the plastic deformation, micro-plowing, micro-cutting, and micro-cracking mechanisms. Fig. 2 gives a typical morphology of the abraded surfaces of UHMWPE.

The force acting on a unit area of the abrading surface resulted from the centrifugal force and the initial force of the abrasive particles. The centrifugal force was dependent upon the compactness and the movement velocity of the abrasive material. The inertial force was related to the movement velocity of the abrasive material when the compactness of the abrasive material was constant. When the compactness of the abrasive material and the sliding velocity were kept constant, the force acting on a unit area of the abrading surface can be considered constant. The stress acting on the abrading surface consisted of the components of the compressive stress and shearing stress. If there were n abrasive particles contacting the abrading surface per unit area, the average shearing stress (τ_m) on the unit abrading surface

Figure 2 SEM photograph of the abraded surface of UHMWPE against quartz sand of size 0.420–0.840 mm at the sliding velocity of 2.35 m/s.

was the sum of the shearing force ($\tau_i, i = 1, 2, \ldots n$) generated by the n contacting abrasive particles, that is, $\tau_m = \sum_1^n \tau_i / n$. There were more abrasive particles contacting the abrading surface per unit area for the smaller size of abrasive particles than those for the larger size of abrasive particles. Therefore, the real shearing stress acting on the abrading surface by a larger abrasive particle was higher than that by a smaller abrasive particle. As a result, the larger abrasive particles tended to enhance the plastic deformation, micro-plowing, micro-cutting, and micro-cracking procedure of the abrading surface layer because of the higher real shearing stress for the larger abrasive particles. Therefore, the larger abrasive particles resulted in more abrasive wear. The centrifugal force and the inertial force acting on the abrading surface against abrasive particles increased with the sliding velocity. So, the abrasive wear of the composites became faster when the sliding velocity was higher.

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