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ANOVA AND REGRESSION MODEL OF SLURRY EROSION PARAMETERS OF A POLYMERIC SPRAY- PAINT FILMS

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Abstract: *In this paper, slurry erosion behavior of a polymeric paint film coated on steel and impacted with silica was investigated. The investigated coating was commercially available as 'Kendo' which are used in automobile paint systems to provide protection to both mechanical and corrosive damage. Slurry erosion tests were conducted on the samples to investigate the effect of the common slurry erosion parameters: slurry concentration, impact angle, and impact velocity on the mass loss of the paint material as response. ANOVA was used to study the contribution of the individual parameters, and regression equations were developed to predict the response (mass loss). The results revealed that the slurry erosion was found to be increased by increasing the slurry concentration and impact velocity. In addition, the increase in the impact angle resulted the increase of erosion until the angle reaches 66^o. Moreover, ANOVA analysis illustrated that slurry concentration and impact angle are the significant influencing parameters on the mass loss of the paint material, contributing of impact velocity was less significant. A linear regression model was developed based on the ANOVA results. The developed regression models were validated with the experimental results and found to be feasible.*

Keywords: *Slurry erosion; ANOVA; Regression; Automobile paint coatings, Kendo spray-paint*

1. INTRODUCTION

Erosion is a form of damage occurs on the surface of impacted materials, experienced by a solid body. When the solid body is laden by a fluid and impinges the surface of the material, in this case it is called slurry erosion. Nowadays, slurry erosion becomes a serious problem in many industrial applications because of the performance, reliability, and service life time of slurry equipment. Some of the industrial applications which have severe impact of slurry erosion problems are petroleum tubing and equipment system, solid-liquid hydrotranspotration systems, coal liquefaction plants and industrial boilers, hydraulic turbines, airplanes engines and bodies and so on [1]–[6].

Coatings and surface heat treatments techniques are very common methods used to protect the surface of materials against the erosion and corrosion damages [7]–[11]. In the field of means of transportation such as airplanes, railways, cars, etc., designers seek to protect the outer surfaces of these bodies from the impact of dust on them while traveling at high speeds, and protect them from the impact of corrosive damage. To protect these surfaces from mechanical and electrochemical corrosion, many techniques are used to increase the surface resistance against erosion such as carburizing, boronizing, High Velocity Oxygen Fuel (HVOF) thermal spray coating, etc. [7], [10]–[17]. The studies that used these techniques might enable to reduce the erosion rate and increasing the surface hardness, however, using these techniques are still expensive, and needs exclusive equipment and takes long-time to perform. Moreover, using these techniques pollutes the environment and have many risks on the workers. In addition, they are not suitable for complex shapes such as the external parts of vehicles bodies.

Alternatively, manufacturers utilize polymer paints as an easy and cheap method and, meanwhile they provide acceptable resistance to both mechanical and corrosive damages [18]. However, due to the variety of polymer paints types which are used in this industry, these paints should be, firstly, studied and investigated against the erosion and corrosion tests before they approved for use. The main common factors that affect the paint of vehicles, for example, the impact velocity, concentration of dust/solid particles, and impact angle. Therefore, in this study, the focus will be on these factors to investigate the significant of each factor on the mass loss of paint using experimental analysis and Analysis of variance (ANOVA) technique.

(ANOVA) is a widely used technique in the field of statistics being the appropriate procedure for testing the equality of several means. The objective of the ANOVA procedure lies mainly in estimating and testing hypotheses about the treatment effect parameters. The usual t- test cannot be used to test the joint hypothesis that the true partial slope coefficients are zero simultaneously.

In this paper, we use The Whirling- Arm Slurry Erosion Test Rig (WASET) which was designed by Aboul-Kasem et al. [19], [20] to investigate the impact of the three factors, namely slurry concentration, impact angle, and impact velocity at different levels on the mass loss of a polymer spry-pain material, commercially known as “Kendo”. Then, we use the results to identify the significant factors affecting the mass loss of a polymer spry-pain. We apply ANOVA to reach our objective and the significant factors comprise the independent factors of the developed regression model hereafter. The discrepancies between the experimental results and the developed regression model are calculated to test the model validity.

The remainder of the paper is organized as follows. Section 2 demonstrates the experimental work; section 3 gives the results and analysis; section 4 presents the discussion.

2. EXPERIMENTAL DETAILS

2.1 Test-rig description

The Whirling- Arm Slurry Erosion Test Rig (WASET) shown in Fig. 1 is used to investigate the slurry erosion parameters which are the impact angle, concentration, and impact velocity on the mass loss of the paint material. The full description of the device can be found in [10], [11], [19], [20]. The main units of the used device are the slurry unit, the specimen rotational unit, and the vacuum unit. The solid-particles with tape water are mixed in the slurry tank, then this mixture is going to another slurry tank (small one) inside the vacuum chamber. This small tank should be kept full of slurry all the time to let the falling velocity of the slurry is constant, v_1 = 1.67 m/s. The other horizontal component of impact velocity is coming from the specimen rotational unit, v_2. Therefore, the resultant impact velocity, v, will come from both of v_1 and v_2, as shown from Fig. 2. The impact angle, $\vartheta\ (= \vartheta_o + \acute{\vartheta}\ )$, is measured from the plan of the specimen to the vector of the resultant impact velocity, v. The vacuum unit is used to reduce the aerodynamic effect during the rotation of the specimens inside the chamber, all other details and descriptions can be found in these researches [19], [20].

2.2 Impact angle versus the exposure time

The most important difference in this new designed device (WASET) is the comparison process among the impact angles. In this apparatus, it is not correct to compare among the impact angles versus a constant exposure time, as shown in Fig. 2. The amount of erodent (solid particles) which strikes the surface of specimen is differ from impact angle to another, when they subjecting to the same test time. Therefore, a set of mathematical calculations are carried out to find a relation between the mass of erodent which will strike the specimen as a function of the impact angle and the exposure time; the following equation shows this relationship:

$$m_p = \left[L\sin(\theta_o) A_n + \frac{LCos(\theta_o)\, Q}{\pi DN} \right] C_w\, \rho_w \quad (1)$$

Where,

ϑ_o: the angle between the top surface of specimen and the horizontal plane.

L: is the length of wear specimen surface, m

A_n: is the area of orifice, m^2

C_w: is the weight fraction of solid particles in water

ρ_w: is the water density, kg / m^3

D: is the rotational diameter of the wear specimen, m

Q: is the volume flow rate of slurry, m^3/min., and

N: is the rotational speed of the wear specimen, rpm.

This equation is used to adapt the corresponding test time at different impact angles. At these test times, all wear specimens will be subjected to the same amount of erodent (solid particles).

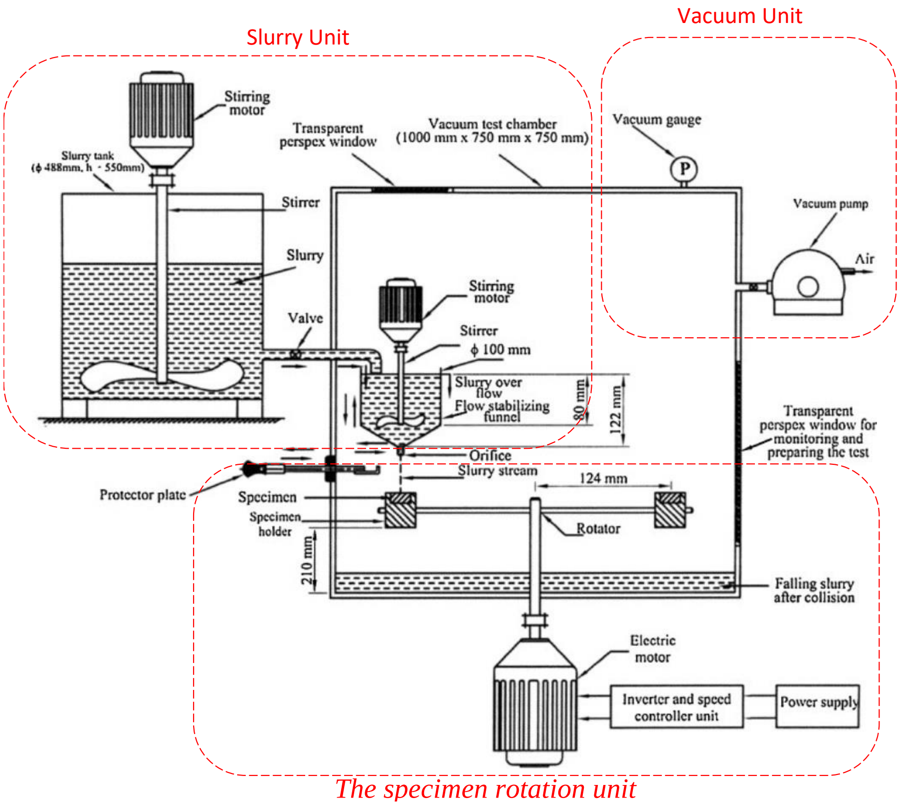

Figure 1. Schematic diagram of the used slurry erosion apparatus

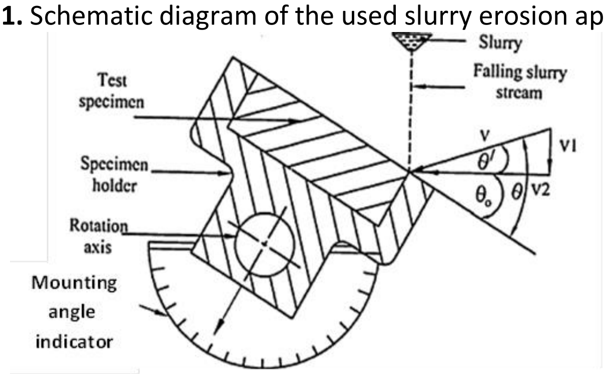

Figure 2. Impact velocity and impact angle

As a conclusion for this part, if the specimens are subjected to the same mass of erodent, say m_p=1.8729 g, then the test times corresponding to some common impact angles, are given in Table 1.

Table 1. Test Times Corresponding to Different Impact Angles for the Same Mass of Erodent (m_p=1.8729 g)

ϑ, deg.	Mass of erodent m_p, g	Corresponding test time, t (min.)
15	1.8729	4.12 = 00:04:07
30	1.8729	2.06 = 00:02:03
45	1.8729	1.44 = 00:01:26
60	1.8729	1.17 = 00:01:10
75	1.8729	1.04 = 00:01:02
90	1.8729	1.00 = 00:01:00

2.3 Painting process

The slurry erosion of the polymeric paint - films was examined through photographing the eroded areas and weighting the mass loss of paint. The used coating is known commercially as "Kendo spray-paint". The test coupons were 10 x 10 x 23 mm^3 steel blocks. The top surface of each block (10 x 23 mm^2) was exposed to polishing process until the surface roughness, R_a, reached about 0.3 µm. After cleaning each block by acetone, a hand spraying was employed from certain fixed height to form a uniform coating thickness, this technique was confirmed by Mehidi et al., [21] and Parslow et al., [22]. Then the test coupons were examined using an optical microscope to ensure the consistency of paint thickness.

As the properties of the used solid particles in erosion studies are very important [18], then, many precautions were taken during this study to let the factor of solid particles properties not included and its effect is constant during all experiments. From these precautions, a single source of solid particles was used, new and fresh particles were used for every experiment to avoid any change in the size due to degradation of particles, the size of used particles was fixed and it was 250 – 355 µm. The used fluid in this study was tap water at room temperature, and the concentration of slurry was 1 wt. %, if not stated unlike that. Finally, specimens were cleaned and weighted before and after each experiment and the average of two mass-losses of two specimens had been reported at each test condition.

3. RESULTS AND ANALYSIS

Table 2 reveals the obtained results with different levels of all studied factors. First, we present the response plots, then the ANOVA results, after that the linear regression models and its evaluation.

Table 2. The results of mass loss under different levels of the studied factors

Trial No.	Concentration	Speed	Angle	Mass loss
1	1	15	10	0.00
2	1	15	20	0.10
3	1	15	30	0.20
4	1	15	45	0.30
5	1	15	60	0.60
6	1	15	75	0.70
7	1	15	90	0.85
8	1	5	30	0.10
9	1	5	45	0.10
10	1	5	60	0.20
11	1	5	90	0.20
12	1	10	30	0.10
13	1	10	45	0.20
14	1	10	60	0.20
15	1	10	90	0.30
16	1	15	30	0.10
17	1	15	45	0.10
18	1	15	60	0.20
19	1	15	90	0.20
20	2	15	30	0.25
21	2	15	45	0.30
22	2	15	60	0.35
23	2	15	90	0.40
24	3	15	30	0.30
25	3	15	45	0.35
26	3	15	60	0.40
27	3	15	90	0.50
28	5	15	30	0.50
29	5	15	45	0.70
30	5	15	60	0.90
31	5	15	90	1.10

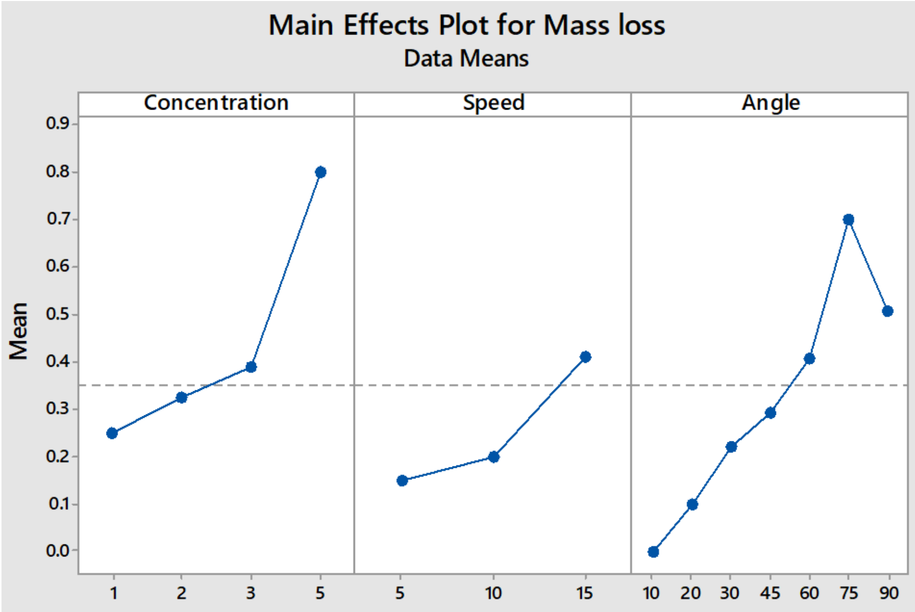

Figure 3. The main effect of the slurry concentration, speed, and impact angle on the mass loss

Table 4. Comparison between the obtained results and the experimental results

	Impact angle	Slurry concentration	Mass loss (Experimental)	Mass loss (from model)	Error (%)
1	45	1	0.1	0.19	-9
2	60	2	0.35	0.39	-4
3	30	3	0.3	0.35	-5
4	60	5	0.9	0.91	-1

3.1 Response plots

Figure 3 depicts the main effect of the studied factors on the response namely the mass loss. The observation of response plots depicts that the increase in the erosion factors increases the erosion rate. By increasing the speed and concentration of slurry, the mass loss is increased drastically, while increasing the impact angle results in increase the mass loss till maximum value, at impact angle 66^{o}, further increase in the impact angle has not such effect. This observation is quite consistent with the study of Joshi et al. [21], but they used the slurry pot erosion test.

3.2 ANOVA

In this section, we statistically test if the impact angle has a significant effect on the mass loss or not. Table 3 concludes the ANOVA of the experiments done in terms of the impact angle and the mass loss. It can be concluded that the impact angle and slurry concentration have a significant impact on the mass loss. However, the speed has no significant effect on the mass loss.

Table 3. ANOVA of the impact angle and the mass loss

Factor	SS	DOF	F-value	p-value
Speed	0.08766	2	1.93	0.172
Angle	0.62544	6	4.59	0.005
Concentration	0.69794	3	10.25	0.000
Error	0.43121	19		

3.3 Linear regression model

We generate a regression model between the slurry concentration, impact angle and the mass loss. The resulted regression model was developed using MINITAB, and it is as follow:

$$Mass\,loss = -0.1671 + 0.1217 Concetration + 0.00524 Angle \qquad (2)$$

The coefficient of slurry concentration is the highest, followed by the impact angle. The interaction effect is negligible, and this confirms the results of the experiments.

In order to validate the regression model, confirmation tests were conducted as shown in table 4. The prediction error is calculated as the difference between the experimental value and the predicted value. The error is quite acceptable for such weight- sensitive experiments. Thus, the developed model is considered to be feasible to predict the slurry erosion values within the range of the experimental conditions.

4. DISCUSSION

From the slurry erosion experiments, it is clear that concentration of slurry has a significant influence on the mass loss, by increasing the concentration of slurry, the number of impacting solid particles is increased. Therefore, the number of impacts will be increased causing higher damage on the surface, and this damage is leading to an aggressive mass loss. The impact velocity had the same trend of slurry concentration but with no significance on the mass loss. By increasing the impact velocity, the mean of mass loss is increased also, this may be interpreted in light of the kinetic energy of the impacting. As it is known that the kinetic energy is proportional with square velocity. Therefore, the impacting velocity increases the impacting force leading to deeper indentation, microcutting or ploughing of the solid particles in the surface material, depending on the accompanied mechanism at the impact angle, causing the increase in the mass loss [16], [23]. However, the effect of the impact angle has not the same trend, in the beginning the mass loss is increased by increasing the impact angle till the maximum value at the impact angle 66^o, but further increase in the impact angle has not such effect. The peak mass loss at this impact angle indicating the semi-ductile nature of the studied painting material [24].

5. CONCLUSIONS

This paper presented a slurry erosion experimental and statistical study. The statistical analysis illustrated that the concentration and impact angle are the significant factors; however, the speed is not significant. Moreover, slurry concentration has the most significant effect on the erosion of the painted specimens. The experimental results showed that the peak erosion occur at the angle of 66^o. A regression model was developed to predict the mass loss with the significant factors, and it was validated to be feasible to calculate and predict the mass loss under different values of concentration and impact angles.

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