Tribology in Industry

Investigation of Abrasive Wear Performances of Different Polyamides by Response Surface Methodology

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A B S T R A C T

This study presents the investigation of abrasive wear performances for polyamides using a Response Surface Methodology (RSM). Tests were carried out in a pin-on-disc using various conditions against SiC abrasive cloth. Box-Behnken Design of RSM was adopted to study the effect of control factors like load, speed and tensile strength of the tested samples on the volumetric wear rate. The experimental results indicated that the volumetric wear rate increased with increasing load, speed and decreased with increasing the tensile strength, but material property was more effective than other factors. Furthermore, the results of analysis of variance showed that tensile strength was predominant factor on the abrasive wear rate, followed by load and spindle speed. The contributions of tensile strength, load and speed were about 33.55 %, 24.45 % and 21.87 %, respectively, while the contribution of square and 2-way of interaction was about 3.04 % and 11.23 %, respectively.

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1. INTRODUCTION

Due to their combination of higher mechanical, physical, chemical/corrosion resistance and tribological properties in addition to their easy processing, polymers are widely used for numbers of engineering applications such as bearings, bushes, gears, cams, rollers and bearing cages against metals, polymers and ceramics [1].

Polyamides (PAs) are polymers which contain repeating amide bonds, known as cast nylons. Polyamide PA6 and PA66 are the most widely preferred for engineering and industrial applications such as chemical, mining, ship, package, automotive, manufacturing/mechanical and tribological fields [2].

When there is contact between the sliding pairs of materials, the friction and wear problems

always takes place. For industry, however, the most of the wear problems encountered are abrasive wear about 60 % of total cost [3]. Abrasive wear, which is the most important one, occurs with the sliding of a hard material over a softer material under load, while surface asperities of harder material remove the softer material [4].

The wear of polymer is a complex phenomenon that depends upon many factors like types of material, geometries, surface property, mechanical property, crystallinity, glass transition temperature, orientation and test conditions [5-21]. Under dry conditions, significant improvements are achieved for the dry wear of polymer based materials. However, there are a limited numbers of studies related to the abrasive properties of the polymers. Pejakovic et al. [22] studied the abrasion wear resistance of commercially available selected polymer materials using SiO_2 abrasives. The polyethylene-based samples showed the lower wear resistance while the polyurethane-based samples indicated that abrasion behavior depended on both hardness and elongation. Shipway and Ngao [23] investigated the abrasive wear behavior of polymeric materials and the results indicated that the polymer type determined the wear property. Funda et al. [24] developed the empirical model using RSM for the prediction weight loss of polyoxymethylen (POM) under abrasive sliding. The weight loss increased with increasing load and sliding distance. Sagbas et al.[25] also investigated the wear behavior of POM in terms of load and sliding distance, but RSM and artificial neural network (ANN) method are compared. Unal et al.[26] studied the abrasive wear behavior of different polymers. For all tested polymers like POM, UHMWPE, PA66 and its composites, the wear rate increased linearly with abrasive distance and grit sizes. Several other studies indicated that Taguchi approach was applied on the abrasive wear behavior of the polymeric materials including glass/carbon fibers/fabrics and SiC particles [27-32,35-39,42-45].

There are number of studies on the dry wear behaviour of polymers and its composites [5-21] while there are some works on abrasive

wear for polymers and its composites [22-26; 33-39;42-45], but no study is conducted on the abrasive wear behaviour of PAs using a RSM method, especially for heavy loading conditions. Therefore, the aim of this work is to determine the dry wear behavior of different casting polyamides by a RSM under SiC emery papers and multi-linear regression equation is developed to predict the wear behaviour of polyamides.

2. EXPERIMENTAL

2.1 Materials

Due to their excellent properties like toughness and shelf life, and recyclability, thermoplastics are found in some applications, particularly for bearings and bushings. The tribological behavior of some unfilled thermoplastic polymers like PA6G (cast version-white), PA6E (extruded version-black) and PA6G plus oil (oil-filled cast version-green) were studied using a pin-on-plate type of tribometer, sliding against AISI 4140 hardened steel, but SiC abrasive was fixed on the steel. These polyamides were provided from Quadrant Engineering Plastics Group, while Ertalon and Nylatron were also referred as trade names. PA6 polyamide refers"Ertalon 6 SA", PA 66 polyamide presents "Ertalon 66 SA" and PA 6+oil polyamide indicates "Ertalon LFX"types. PA6G (PA6) is a type of cast polyamide with outstanding properties and it has many properties that no other material has in combination. PA6E (PA66) is successfully used in place of metals in a number of machines such as packaging, textile, metal working, chemicals, construction like gears, bearings, bushes, etc. PA6G plus oil grade (PA6+oil), which is a wear resistant engineering plastic with a low coefficient of friction, it can be preferred in applications where dimensional stabilities are required. Lubricants and some wear increasing additives are added during production stage to turn from PA6G to PA6G plus oil one. Integrated into the material, lubricant additives become inseparable and homogenous components. Some mechanical and physical properties of PAs are shown in Table 1 [Data sheets of Quadrant Engineering Plastic Producs].

Table 1. Chemical, physical and mechanical properties of PAs.

Some properties (Mechanical, physical and chemical)	Material's types		
	PA6G	PA6E	PA6G+ oil
Density (gr/cm^3)	1.14	1.14	1.135
Thermal conductivity (W.m^{-1}.K^{-1})	0.28	0.28	0.28
Rockwell hardness (N.mm^2)	M85	M88	M82
Compressive strength at % 5 (GPa)	87	110	85
Tensile strength (MPa)	80	93	73
Tensile strain at break (%)	70	50	25
Elastic modulus (MPa)	3300	3550	3000
Water absorption (%)	2.6	2.4	2
Melting points (°C)	220	260	225
Max allowable service temperature (°C)	160	180	165

2.2 Experimental design

Response surface methodology (RSM) uses a statistical measure of performance to evaluate the optimal parameter settings. In the present work, three parameters such as load (L), speed (S) and tensile stress (T) on the volumetric wear rates (VWR) of the polyamides as control parameters are studied using a Box-Behnken Design (BBD). The BBD requires minimum three levels of each factor for the calculation of the regression coefficients. The total 15 experimental trials are carried out according to the BBD design matrix. In this method, input parameters are controllable and multi-factor analysis is made for optimization of dry wearing control parameters for given responses. The data are combined with the different variables according to the center point of the cube edge at 12 positions and the center of the cube at 3 repetitions. Their codes and levels of control parameters are shown in Table 2.

Table 2. Control factors and their levels (un-coded).

Symbol	Control parameters	Unit	Level 1	Level 2	Level 3
L	Applied load	N	7	17.5	28
S	Sliding speed	m/s	0.33	0.66	0.98
T	Material tensile strength	MPa	73	80	95

This table indicates that the experimental plan has three levels. Each combination of experiments is repeated three to acquire more accurate results in the process.

2.3 Wear test

Experiments are carried out on polyamides using a pin-on-disc wear testing configuration in accordance with ASTM standard. Counter surface material is an AISI 4140 steel disc by 14 mm in thick, which was heat-treated to give a surface hardness of 59-63 HRC. The counter surface material was ground to a surface finish of approximately 0.40 μm center-line average, but SiC abrasives are attached on the smooth steel disc. The pin is slid in a circular motion against the SiC emery paper on the hardened steel to perpendicular to sliding direction. PA bars are machined into small cylindrical shape with a lathe machine. The pin specimen is fixed to the specimen holder by setting screws. The diameter of the pin is 8 mm with 15 mm in length. Wear tests were carried out at different sliding speeds under three loads of 7, 17.5 and 28 N. The normal load is applied through a spring and lever system. Sliding radius is about 130mm while sliding distances are about 15m, 30m and 45m, respectively. Abrasive paper type was SiC and its grade was 400 grit size. The material loss of samples is calculated from the weight loss method. After the test, the wear pin is cleaned in acetone prior to and after the test, then dried and weighed on a microbalance with 0.1 mg sensitiveness. Each test is performed with a new track of plate. Three replicates are carried out for each material and the results are averaged from the three test runs.

3. RESULTS AND DISCUSSION

3.1 Analysis of wear

The results of the experimental data were analyzed using MINITAB 17 software. The results of average volumetric wear rate for the dry abrasive wear behavior of polymers like PA6G, PA6E and PA6G+oil using BBD method were illustrated in Table 3 and Fig. 1. The tests relevant to this table were carried out at indicated parameters. The experimental plain and trial conditions were also included in this table. Theoretical results and experimental results were compared in this table in addition to providing average errors. It was obvious in Table 3 that the volumetric wear rate of PA6E polymer was smaller than those of other polymers. This was attributed to the penetration ability of steel disc

was lower for this sample because its increased tensile strength and modulus of elasticity (see Table 2).

Table 3. Experimental plan, run and abrasive dry wear results for the volumetric wear rate.

| Exp. Run	Main control factors			Wear rate		
	L, N	S, m/s	T, MPa	Volume. wear rate (mm³/m)	Theor. wear rate (mm³/m)	Error, %
1	7	0.33	83	1.61616	1.8759	13.85
2	28	0.33	83	3.06220	2.9761	2.89
3	7	0.98	83	0.81033	0.8964	9.60
4	28	0.98	83	2.19365	1.9339	13.43
5	7	0.65	73	1.80046	1.4542	23.8
6	28	0.65	73	3.26776	3.2674	0.010
7	7	0.65	93	0.94630	0.9466	0.037
8	28	0.65	93	0.92503	1.2712	27.23
9	17.5	0.33	73	2.74676	2.8332	3.05
10	17.5	0.98	73	2.26557	2.5256	10.29
11	17.5	0.33	93	2.54474	2.2846	11.38
12	17.5	0.98	93	0.65689	0.5704	15.15
13	17.5	0.65	83	1.77210	1.7207	2.98
14	17.5	0.65	83	1.68704	1.7207	1.96
15	17.5	0.65	83	1.70299	1.7207	1.02
				Average error (%)		9.112
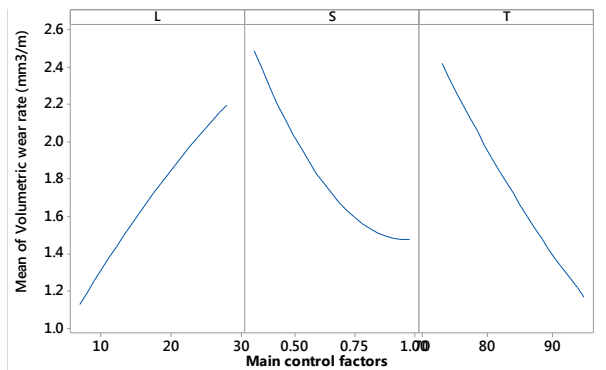
Fig. 1. Mean plot for mean volumetric wear rate of PA6G, PA6E and PA6G+oil types of polyamides.

Therefore, the formation of heat was prevented by this property between the components that rubbed against each other. The wear became a smaller with the decreasing the elongation. The previous work on the dry wear behaviors of polyamides revealed that optimal factor was obtained for PA6G plus oil type of polyamides against hardened steel [21]. This might be due to testing the lubricated type of sample against the hardened smooth steel and resulting in

formation of transfer layer on the counter face. The sliding velocity and load influenced the frictional heating of polyamide (N6), thereby increasing the wear rate due to increase in the temperature [1]. However, for others polymers like POM, UHMWPE, PA66 and its composites, the wear rate increased linearly with abrasive distance and grit sizes [6,26].

Figure 1 shows the variations of the volumetric wear rate versus main control factors for the tested polyamides. The mean response referred to the average values of the performance characteristics with different levels. It can be seen from this figure that among the control factors, the factor T of tensile strength showed the highest effect on the wear rate because of decreased penetration effect of SiC abrasives associated with increased strength of the polyamide, followed by the factor L of applied load and the factor S of sliding speed, respectively (Fig. 1). On the contrary, the abrading distance was more effective on the wear of the polymer composites [39], but the load was effective for the carbon reinforced composite [42], while the recent work by Şahin [20,21] indicated that the abrasive size, load and sliding distance had great effects on the weight losses for cast polyamide samples. Furthermore, a linear increase was observed with increasing the load, while a linear decrease was evident with increasing the tensile strength by obeying the Archard's equation. Among the tested PAs, the PA6GE samples indicated a better wear performance than those of the others due to higher tensile strength and modulus. The similar finding was reported for the wear resistance of polyamides [33]. It is noted that the sensitivity of the load was slightly larger than that of the speed, but the wear rate tended to be left from the linearity with increasing the speed due to the increased the temperature at the interface, hence the rubbing pairs leading to thermal softening of the resin. In addition, Fig. 2 shows the interaction plots for the wear rate of the polyamides as a function of main control factors. It is clear that L*S did not indicate any interaction. However, there appeared some interactions for L*T and S*T. This, especially increased with the load level 3 in addition to speed level 3. This might be due to changing the mechanism from abrasive to adhesion/delamination and resulted in a higher wear rate because abrasive wear was dominated for the lower condition while adhesion or delamination appeared for the heavy condition.
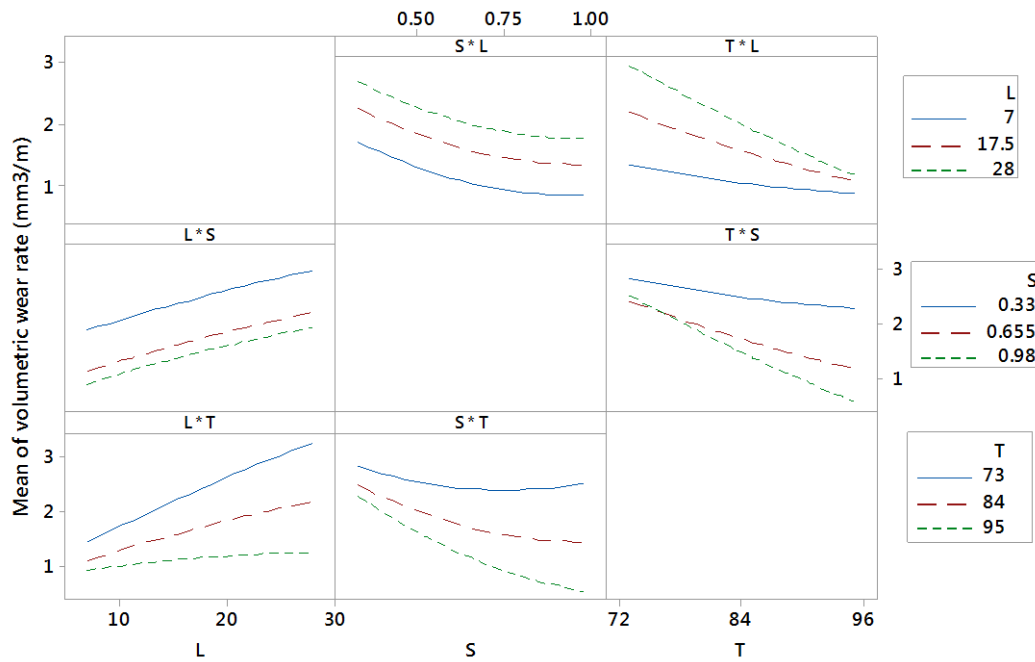
Fig. 2. Interaction plot for mean volumetric wear rate values for the polyamides.

Figure 3 shows the surface plot of the volumetric wear rate vs.interaction parameters under all applied parameters. Figure 3a indicates the VWR vs.L,T while Fig. 3b shows the VWR vs.L,S and Fig. 3c indicates the VWR vs. S,T parameter, respectively. These figures also confirmed the previous Fig. 1, indicating the dominant factor of tensile strength, which is followed by the load.

(c)
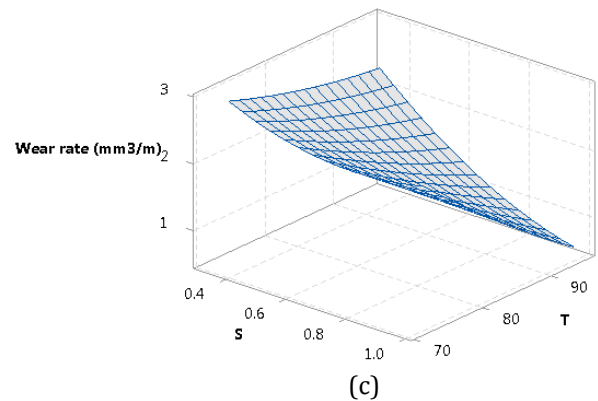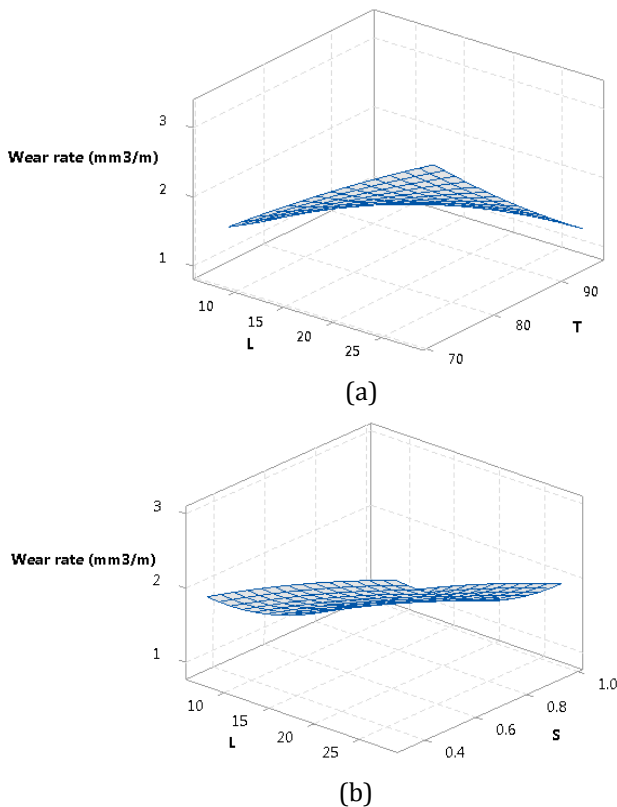
Fig. 3. Surface plot of volumetric wear rate vs.interaction parameters. (a) VWR vs.L,T; (b) VWR vs.L,S, (c) VWR vs.S,T.

(a)

(b)
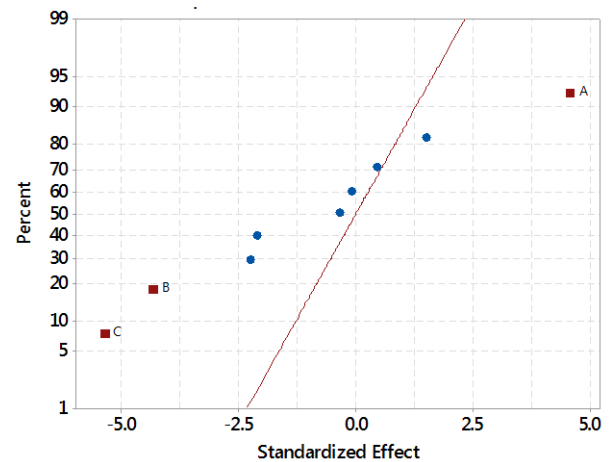
Fig. 4. Normal plot of standardized effect of process parameters on the average volumetric wear rate. A,B,C factors and   Significant ■ Not siginificant ■.
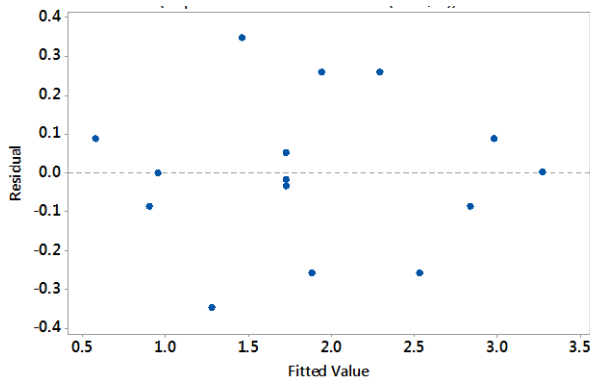
Fig. 5. Residual versus fit values on the volumetric wear rate of the polyamides.

Figure 4 shows the normal plot of standardized effect of process parameters on the average volumetric wear rate of the polyamides. It visually exhibited the degree of effect of each parameter in the obtained results. This figure indicated that the main control factors of A, B, C had a statistically significant effect on the wear of the tested samples. Moreover, Fig. 5 indicates the residual versus fit values on the wear rate of the polyamides. The residual distributed a uniformly around the dot line and its fitted values is lower than 4 while the residual value is about 0.35.

3.2 Analysis of variance (ANOVA)

The ANOVA was used to investigate which design parameters significantly affect the quality characteristic for the wear rate of the polyamides. The results for the sliding wear behavior of polymeric materials under SiC abrasive papers were analyzed and listed in Table 4. This analysis was performed for the 5 % significance level, that is, for the 95 % confidence level. It is clear that factor T had a statistical and physical significance on the wear rate because P-value was lower than 0.05 value, followed by factor L and factor S, respectively.

P-value indicates the degree of influence from each factors. It could be observed that factor T (P-value = 0.003) had a significant effect, followed by factor L (P-value = 0.006) and factor S (P-value = 0.007), respectively. Other factors like square (P=0.514), and two-way interaction factors (P=0.12) did not indicate any significant effects on the dry wear properties. However, the lack of fit value is equal to 0.011, which was lower than 0.05 value. Besides, a contribution of each factor (Pc) on total variations in the last column can be

calculated and shows a degree of influence on the wear results. The contributions of T, L and S were about 33.55, 24.54 and 21.87 %, respectively. However, sliding/abrasive distance was the wear factor that had the highest statistical influence on the dry wear of composites [22,33,35].

3.3 Regression analysis

The correlations between the control parameters like load (L), speed (S), tensile strength of the tested samples (T) and wear rate were found by multiple regressions. The correlations were as follows:

Regression equation in uncoded units,

$$Volumetric\ wear\ rate,\ VWR\ (mm^3/m) = 1.72$$
$$+ 0.534\ L + 4.29\ S - 0.052\ T - 0.00054\ L*L$$
$$+ 2.45\ S*S + 0.00074\ T*T - 0.0046\ L*S \qquad (1)$$
$$- 0.00354\ L*T - 0.1082\ S*T$$

Where *VWR* means is the average volumetric wear rate; Eq. (1) indicated that the wear rate increased with the load and the sliding speed, but it decreased with the increasing material's tensile strength for testing the composites.

Table 4. Analysis of variance for the wear property of various polyamides.

Source	DF	Adj.SS	Adj.MS	F-Value	P-value	Pc (%)
Model	9	8.797	0.977	8.99	0.013	4.17
Linear	3	7.463	2.487	22.87	0.002	79.8
L	1	2.284	2.284	21.01	0.006	24.5
S	1	2.043	2.043	18.79	0.007	21.8
T	1	3.134	3.134	28.82	0.003	33.5
Square	3	0.284	0.094	0.87	0.514	3.04
L*L	1	0.013	0.013	0.12	0.743	3.04
S*S	1	0.248	0.248	2.28	0.191	2.65
T*T	1	0.019	0.019	0.18	0.686	0.21
2-Way Inter.	3	1.049	0.349	3.22	0.120	11.2
L*S	1	0.0009	0.0009	0.01	0.928	0.00
L*T	1	0.553	0.553	5.09	0.074	5.92
S*T	1	0.494	0.494	4.55	0.086	5.29
Error	5	0.543	0.108	5.82		
Lack of fit	3	0.539	0.179	88	0.011	5.77
Pure error	2	0.0040	0.002			
Total	14	9.341				100

The higher value of regression coefficients would be directly translated into the higher effect of the variables to the response. The model had a R^2 value of 94.1 %. The estimated wear rate of the composites was calculated using

Eq. (1) with the substituting the recorded values of the variables. In the predicting of the wear rate, average error was found to be lower than 9.1 %. The use RSM on UHMWPE was successfully developed a model that the filler loading, load and sliding speed had a significant effect on the wear rate and COF of UHMWPE [36]. The second order regression model showed that the load was higher effect than speed and materials type, respectively [26].

3. CONCLUSIONS

The abrasive/dry sliding wear behavior of three different types of polyamides was investigated in a pin-on-disc tribometer against SiC abrasive clothes using the RSM method under different parameters.

The following conclusions were drawn:

1. The abrasive sliding wear properties of various polyamides samples were determined using a Box-Behnken Design (BBD) of response surface methodology. The volumetric wear rate decreased with increasing the tensile strength and speed, but it increased with the load.

2. Among the tested samples, PA6E samples showed the higher wear resistance than that of others at all conditions because of higher tensile strength and modulus of elasticity.

3. ANOVA exhibited that the tensile strength was the most effective factor on the wear rate of PAs (P=33.55%), followed by the factor L (P=24.45%) and the factor S (P=21.87%), respectively.

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