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Utilizing Taguchi Experimental Design for Optimizing Effective Parameters in Tire Vulcanization

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***Abstract*—**In order to convert natural rubber or related polymers to material with varying physical properties such as elastic modulus or durability, a chemical process named sulfur vulcanization is needed. This can be either done by heating sulfur or sulfur-containing compounds. The main goal of this process is to produce untreated natural rubber latex that can be the main source of manufacturing for several rubber producers. Temperature, pressure, and time are considered as three crucial factors in the tire vulcanization process. The present study is an attempt to optimize these crucial parameters, with the aim of achieving maximum tire modulus using Taguchi experimental design. The results revealed that the optimal parameter values are as follows: a temperature of 170 °C, a pressure of 110 bar, and a time duration of 230 seconds. Under these optimized conditions, the obtained tire modulus reached 8.8 kgf.

***Keywords*—**Rubber vulcanization, experimental design, Taguchi, polymers.

I. Introduction

THE creation of crosslinks within the polymer matrix is a fundamental determinant of the characteristics of rubber. It has been more than a thousand years since the discovery of rubber. There are two types of rubber: natural and synthesis. The reason for using synthesis rubber is the lack of natural rubber to produce the required products. At high temperature, natural rubber can react to form crosslinks. Therefore, it can completely change from a plastic state to an elastic state. The polymer chain has partially unsaturated bonds, or it is completely composed of monomers with double bonds.

During the vulcanization process of raw rubber, crosslinks are formed. Essentially, vulcanization is a process that completely transforms raw rubber into an elastic state, enabling its utilization as components for industrial rubber products.

Various natural and synthetic rubbers are used in tires, such as polystyrene butadiene, polybutadiene, polyisoprene, polychlorobutadiene, polychloroprene, polyacrylonitrile butadiene, chlorobutyl, bromobutyl. Therefore, rubber includes a wide range of raw macromolecular compounds that have the ability to create transverse connections with different systems and curing agents. The formation of crosslinks in elastomeric polymer matrices is a critical process that significantly impacts the properties of rubber. When raw rubber is vulcanized, crosslinks are created, transforming the raw material into an elastic state suitable for use in various industrial rubber components. Vulcanization enhances tensile strength, modulus, hardness, wear resistance, and resilience, while reducing elongation, thermal waste generation, compressive strength, and solubility. The density of crosslinks plays a vital role in determining the tensile strength and tear resistance of rubber. The effects of vulcanization are directly related to the number and length of crosslinks formed. It is important to note that excessive curing can result in elastomers becoming hard and brittle materials. Longer crosslinks (poly-sulfidic) significantly enhance tensile strength, tear resistance, and wear properties, while shorter crosslinks (mono-sulfidic) reduce thermal and oxidative stability and compressive strength. Figs. 1-4 show examples of Tensile, Rheometer Abrasion testing machine and Hardness tester.

Fig 1 Tensile testing machine

Fig. 2 A picture of Rheometer

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Fig. 3 Abrasion testing machine

The agent that creates crosslinks is the sulfur. There are two types of sulfur: Crystalline sulfur and Polymeric sulfur. The reason of using chemical accelerators is to save curing time and reduce the tire's curing temperature. First, accelerators cause the curing reaction to take place in a shorter time and at a lower temperature. Second, in addition to chemical properties, they also give good physical properties to the compound Thirdly, some accelerators also give the tire antioxidant (protective) properties.

Chemical curing agents are usually added at the last stage of compound production. Several accelerators may be used together, they complement each other. At the same time, delayed accelerators are usually used in systems that have a lower safety time.

Fig. 4 Hardness tester

Vulcanization, also known as curing, enhances tensile strength, modulus, hardness, abrasion resistance, and resilience while simultaneously reducing changes in elongation, heat buildup, and solvent absorption. Notably, the density of specific crosslinks significantly impacts tensile strength and tear resistance.

The alterations caused by vulcanization are directly proportional to the quantity and length of these crosslinks. Excessive vulcanization leads to the conversion of elastomers into hard and brittle materials. Longer crosslinks (poly-sulfidic bridges) contribute to enhanced tensile strength, tear resistance, and wear characteristics, while shorter crosslinks (mono-sulfidic bridges) ensure improved thermal and oxidative stability, as well as reduced swellability under pressure.

In the production of tires, advanced automated curing presses are employed. These presses are typically customized for either one or two molds based on their size. Tire molds are positioned within the press, see Figs. 5 and 6. For bias-ply tires, molds are divided into two picks, while radial tires are often manufactured using segmented molds.

Fig. 5 Example of segmented molds

Fig. 6 Example of two pick molds

The tire vulcanization process includes the following stages:

- Transferring of raw green tire using a loader and loading it onto a bead ring.
- Inserting the bladder into the green tire and transferring steam into the bladder.
- Initial shaping pressure, which depends on the size of the green tire and varies between 0.25 to 0.85.
- Secondary shaping pressure and closure within the press with a mold pressure of 75 tons, along with steam injection at 14 bars into the bladder.

At approximately 20 seconds, the flow of the mixture initiates, leading to the formation of the tire's wall and tread pattern. In practice, vulcanization, similar to any chemical reaction, sees the curing rate gradually increase, doubling for every 10 °C increase. This phenomenon is referred to as the vulcanization heat constant. Tire curing characteristics differ from other molded products as they not only transfer heat from the mold surface but also apply heat internally through the bladder to the raw tire.

Temperature, pressure, and time constitute three influential factors in the curing process. The proper application of pressure to the raw tire during vulcanization is of significant importance. This pressure can prevent the occurrence of air bubbles present between the outer tire layer and its carcass, which could potentially result in layer separation during service. Additionally, it is important that sufficient pressure is initially applied during heat initiation since the raw rubber layers might undergo deformation at this stage and require flow to

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compensate for surface irregularities. This pressure can only be exerted internally at the beginning of vulcanization.

For tire production, advanced automated curing presses are employed. In the case of radial tires, shaping the raw tire during manufacturing is essential to ensure correct placement of the belt at the center. For bias-ply and van tires with nylon-threaded components, a post-curing stage is used to prevent tire contraction, and inflation is applied to prevent tire contraction [1], [2]. Given the significance of the tire curing process, this article aims to optimize three key parameters (time, pressure, and temperature) to achieve maximum tire modulus. This optimization process is conducted using the Taguchi experimental design methodology, along with the MINITAB software.

MINITAB is a statistical quality control software suitable for Six Sigma and quality improvement projects. This software is known as one of the specialized statistical software for quality control and raw data analysis, and it is used in many industries, and it can be used to design by analyzing statistical data. In fact, MINITAB software is one of the popular statistical software that has special capabilities in some fields of statistics, including the application of statistics in industry and economics [5].

The Taguchi method is mainly developed to investigate effects on different factors and parameters on the statistical parameters such as mean and variance. In this method, a special set of arrays, which is called orthogonal, controls the statistical process and provide data that influence the process. This method also analyzes the experimental results to identify the optimal value of parameters [5], [6].

II. Experimental Approach

The Taguchi method revolves around selecting significant process parameters and considering multiple levels for each. This method determines the optimal values for these parameters. Subsequently, the Taguchi method employs an orthogonal array design, known as the standard array, to plan the experiments. By using this specialized orthogonal array design, the Taguchi method allows a comprehensive study of all parameters with the least number of required experiments. The appropriate orthogonal array is chosen based on the selected parameters and their levels. Each column in the orthogonal array represents a process parameter, and its levels are assigned to each experiment, with each row signifying an experiment with varying levels of parameters [3]. In the present study, the aim was to assess the effects of key parameters on the tire curing process. The chosen parameters included time, pressure, and temperature, with the rapid test serving as a means to gauge the resulting tire modulus, acting as the output measure. Each factor was considered at three distinct levels, and any potential interactions between them were disregarded. The respective values for these levels are illustrated in Table I. Subsequently, the L9 orthogonal array was used for experiment design, comprising nine experiments, and the experiment design was conducted using MINITAB software [4], [5]. Table II presents the designed experiments along with the corresponding rapid test results. After performing the designed experiments, analysis of variance (ANOVA) was carried out on the obtained results to fulfill the experiment design objectives.

TABLE I
Selected Factors and Their Levels in the Experimental Design

Factors	Factors level		
	+1	0	-1
Time (s)	230	170	110
Pressure (Bar)	130	110	90
Temperature (°C)	190	170	150

TABLE II
Experiment Design Using L9 Orthogonal Array and Corresponding Empirical Results

Test sequences	Input factors/variables and their levels			
	Temperature (°C)	Pressure (Bar)	Time (s)	Force (kgf)
1	150	90	110	0.9
2	170	110	110	8.0
3	190	130	110	7.8
4	170	90	170	8.3
5	190	110	170	7.6
6	150	130	170	1.5
7	190	90	230	7.4
8	150	110	230	7.2
9	170	130	230	7.8

III. Results and Discussion

The findings of the analysis of variance are presented in Table III. By interpreting the data from this table, the significance and relative importance of the examined factors in relation to tire modulus can be discerned. According to the F-test results, the most influential factor on rubber modulus is temperature, followed by pressure, with time demonstrating the least impact.

TABLE III
Results of Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F
Time	2	6.442	6.442	3.221	0.64
Pressure	2	7.909	7.909	3.954	0.79
Temperature	2	42.909	42.909	21.454	4.28
Residual Error	2	10.036	10.036	5.018	
Total	8	67.296	-	-	-

The primary objective of designing the Taguchi experiment was to determine the optimal values for the parameters of time, pressure, and temperature that would result in achieving maximum tire modulus.

Fig. 7 illustrates the variations in modulus values corresponding to different levels of time, pressure, and temperature variables. Analyzing these results enables us to identify the impact and optimal values of the parameters. According to these findings, the optimum temperature value is 170 °C, the optimal pressure value is 110 bar, and the optimal time value is 230 seconds.

In the final stage, employing the optimal factor values (170 °C, 110 bar, and 230 seconds), software estimation yielded a maximum tire modulus of 9.2 kgf. Subsequently, an experiment was conducted under these optimal conditions, and the rapid test result indicated a tire modulus of 8.8 kgf, which showed good agreement between the empirical value (8.8) and the predicted value by the Taguchi method (9.2).

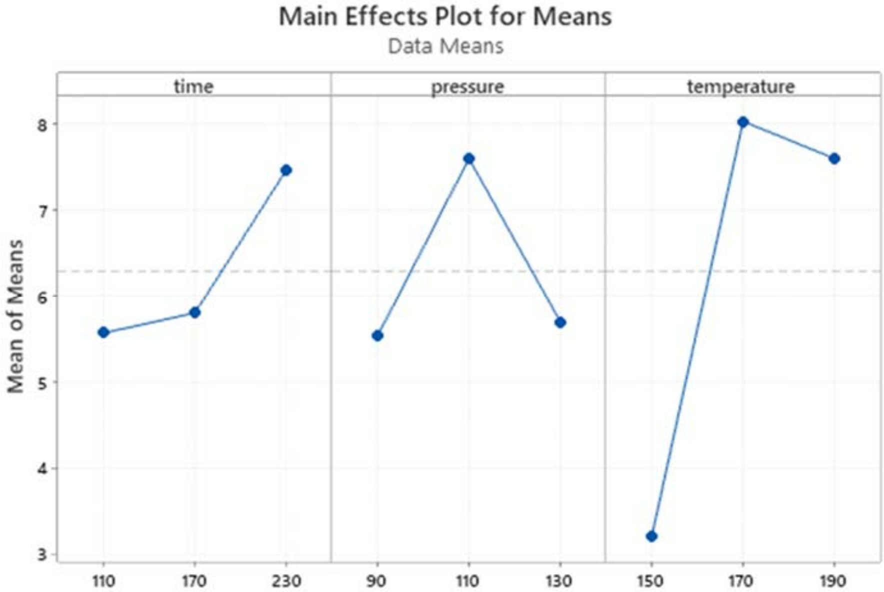

Fig. 7 Outcomes of investigating the effects of various levels of time, pressure, and temperature parameters on tire modulus

IV. Conclusion

Findings in this study suggest that the Taguchi method is a robust method for optimizing tire curing conditions to attain maximum tire modulus 8.8 kgf was achieved.

Based on the performed analyses, it is found that most important parameters on rubber modulus are temperature, pressure and the time of application. Tests results show that the optimal parameter values for these three factors are a temperature of 170 °C, a pressure of 110 bar, and a time duration of 230 seconds.

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