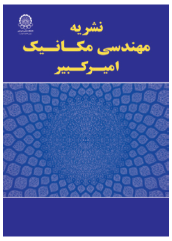

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Tire Hardness Modeling Based on Longitudinal Ultrasonic Velocity Using the Gaussian Process Regression

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ABSTRACT: Non-destructive tests have capabilities to investigate and identify the defects and properties of the test piece without changing the physical and mechanical properties of the sample. The non-destructive ultrasonic test has been used in many investigations to study different material properties such as mechanical and structural properties. The ultrasonic wave propagation velocities have been widely used for metal hardness measurement. In this study, for the first time, non-destructive ultrasonic testing has been employed to measure the hardness of rubber compounds using Gaussian process regression. Eighty-seven samples with different formulations were prepared and vulcanized. After the vulcanization, the compound hardness of the samples and the longitudinal ultrasonic wave velocity through them was measured. The result of Gaussian process regression model shows that this model performs well and able to predict tire hardness. Also, investigating repeatability shows that this method can be a good alternative for conventional hardness testing method in measuring the hardness of rubbers. According to the low time of the test in this method and no need to sample preparation, the proposed method can be used in tire production lines.

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1- Introduction

One of the issues outlined in tire manufacturing is to control formulation, processing stages (from mixing up to curing), and its effects on its physical and mechanical fluctuations. The rubber physical and mechanical properties can be measured by performing different tests after mixing the materials. One of the tests performed to measure compound properties is hardness degree test. In the present research not only the waves' propagation velocity in the rubber compounds was measured and used as an alternative method, but also a relation was modeled between hardness and waves' propagation velocity through support vector machine. Both of the results of the defined method and hardness degree test were then studied. Ultrasonic waves were used to measure metals' hardness and also it was applied for rubbers to study their repeatability in this research.

2- Experimental Details

Non-destructive methods are portable and they can be applied for materials in use. Ultrasonic technique is one of the non-destructive methods widely used for hardness measurement. The ultrasonic pulse-echo method is used to evaluate the hardness difference of the materials. The waves move across the material and the hardness average can be provided in the material bulk. Ultrasonic velocity is related to a specific hardness technique for materials with different hardness degrees [1]. The elastic properties can simply be studied by ultrasonic velocity measurement [2].

In this research, 9 elastic compounds with different formulas were studied. To evaluate the results' repeatability, each formulation was repeated for 6 to 7 times, in which for each of them the necessary samples were made. Table 1 shows different compounds as well as their numbers and curing conditions.

Table 1: Numbers of compounds and curing conditions

Display code	Curing at 145 °C (P)	Curing at 185 °C (R)
H1	0	6
H2	0	7
H3	0	7
H4	0	7
H5	6	6
H6	6	6
H7	6	6
H8	6	6
H9	6	6

Longitudinal wave propagation velocity for each sample is measured by ultrasonic testing. The measurements were done with 4 MHz frequency and at room temperature. The measurements and calculation of averages were repeated 3 times.

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3- Gaussian Process Regression

In the present research, Gaussian process regression was used as it is essential to consider the margin of measurement error. In the defined model, formulation, curing conditions and ultrasonic velocity average are regarded as input parameters for support vector machine and hardness average of rubber compounds is regarded as the output parameter.

4- Results and Discussion

The factors influencing waves' propagation and rubber hardness are also studied in order to determine the parameters influencing waves' propagation in the rubber samples. Density and cross-link density were noted to have a significant influence on the waves' propagation. Cross-link density was calculated by measuring the torque rheometer at 158°C during a time of 6 minutes having the maximum torque difference and minimum torque. When the cross-link density is higher, the maximum torque will be increased. Therefore; as the minimum torque is usually fixed, the torque difference will be increased. As shown in the Figs. 1 and 2, series No. 9 indicates the highest degree of hardness and consequently the highest propagation velocity. Density and cross-link density showed that the density average of the mentioned series is 1,333 g/cm3 and the cross-link density average is 62.75 mol/ m3 which is the maximum averages in the tested samples. The cross-link density averages of series Nos. 2 and 3 are 45.321 mol/ m3 and 45.621 mol/ m3 respectively, which are ranked with the highest hardness after the series No. 9. The research results show that as the cross-link density is increased, the rubber condensation is accordingly increased. The ultrasonic propagation velocity in rubber samples is simultaneously enhanced when the hardness is increased.

Fig. 3 and 4 show the relation between curing model, hardness and ultrasonic velocity of rubber compounds. Indeed, in most compounds when the curing temperature is decreased, the sulphuric cross-link density is increased, leading to enhancing the samples' hardness. The cross-link density increasing during temperature reduction can be assessed by performing the rheometer test and determining the difference torque. Despite the other compounds, compound H9 showed a different behavior, in that both of its cross-link density and hardness were decreased when the temperature was lowered which is considered as an exception in this research. The same result is obtained when performing rheometer testing on this compound and it was confirmed that cross-link density is increased when the temperature is enhanced.

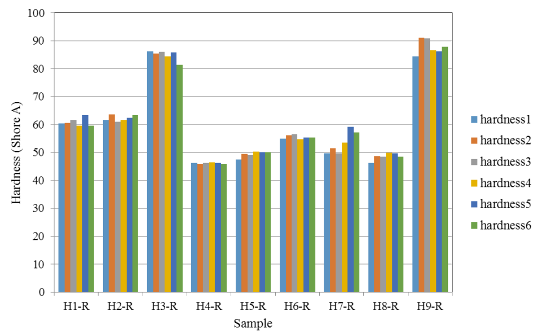

Fig. 1: The repeatability of hardness

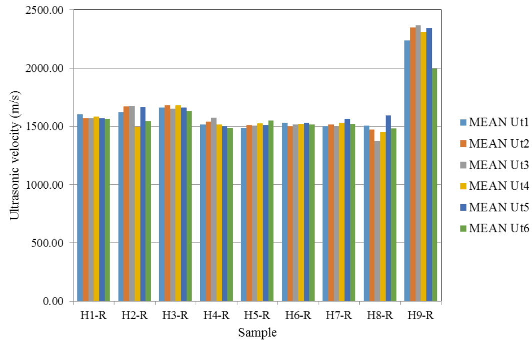

Fig. 2: The repeatability of ultrasonic velocity of rubber

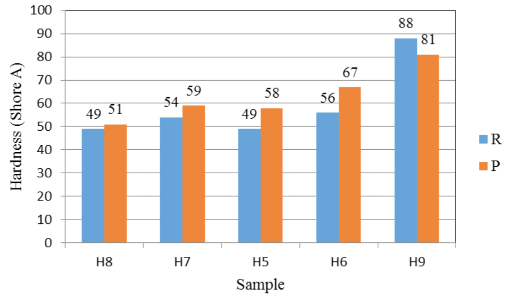

Fig. 3: The relation between curing model, hardness and ultrasonic velocity of rubber compounds

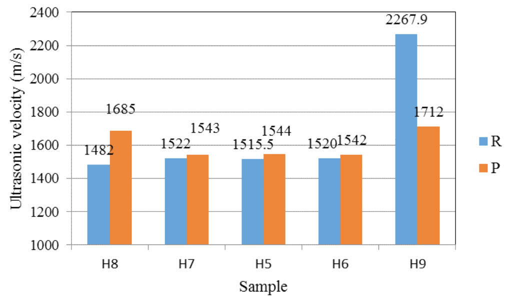

Fig. 4: The relation between curing model, hardness and ultrasonic velocity of rubber compounds

5- Conclusion

As it is not possible to determine the hardness degree of all the manufactured tires of the company, if we succeed to predict the hardness of rubber compounds using ultrasonic technology, it would be regarded as a significant success in the process of tires' quality control.

The results indicate that as the cross-link density of rubber condensation is increased, the ultrasonic propagation velocity, as well as the hardness degree, is enhanced. The results of modeling by Gaussian process regression showed that the presented model is able to predict the process output parameters. Furthermore, according to the results, there was a relation between hardness and ultrasonic velocity while the repeatability was considered.

6- References

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