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IMPACT OF TEMPERATURE ON TYRE HARDNESS

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Abstract. This article deals with the dependence of tyre hardness on temperature. In this study, more than 1 800 temperature-dependent hardness values were measured for 5 samples of summer tyres from different manufacturers and different ages. Using regression analysis, curve equations were determined for each sample. Furthermore, an average curve was determined, which was then applied to the measured values and the error generated by using this average curve was investigated. From the results it is clear that all samples show a polynomial function with a 2^{nd} order polynomial for the temperature range −10 °C to 65 °C. The error of using the average curve reaches values up to 11 % of the average value of the measured hardness of the sample. The lowest error is 2 % of the mean value of the measured hardness of the sample, which corresponds to approximately 1 Shore A. The suitability of using an average curve application depends on the desired output and the required accuracy.

Keywords: Tyre, temperature, hardness, RSE, regression analysis.

1. Introduction

A tyre changes its mechanical properties during its service life. This change in the mechanical properties of the rubber material of the tyre can result in changes in performance and safety under different operating conditions [1]. The tread part of the tyre wears out during its service life. As the tyre wears, the bonding layer, which may vary in chemical composition and material properties, may become exposed [2]. Hardness measurements can be used to determine the change in mechanical properties. During oxidation, the chemical structure of the material changes, which is accompanied by a change in the mechanical properties of the tyre material. The aging or oxidation of rubber material is natural, irreversible and caused by the disruption of the polymer chain of the rubber and the binding of an oxygen atom from the environment [3–5]. To prevent ageing, oxidation-inhibiting additives called antioxidants are added to the tyre material [6]. However, these additives vary according to the manufacturer and model of the tyre. Brown [3] reported in his publication how material properties change over the 40 years of a tyre's age. In article Ho et al. [7] describe that as a tyre is aged, a change in hardness of 0.6 Shore A per month occurs. As reported by Brown in his publication [8], hardness measurement is advantageous mainly because of the economical use of material, the almost non-destructive character of the test, cheapness and simplicity. However, it should be mentioned that repeatability and reproducibility in durometer can be relatively poor, and therefore dead load methods are preferred. The determination of dead load hardness, including microhardness, shall be carried out in accordance with ISO 48.

Hardness is essentially a measure of stiffness and can be related to the modulus of elasticity. The measurement of the hardness of rubber materials, which definitely includes tyres, is well described in ISO 48-4 or its transcriptions in ČSN ISO 48-4 [9]. For the measurement of the hardness of rubber materials with standard hardness, which include tyres, the Type A method with a Shore A unit scale or the IRHD method is used. For rubber materials with specific properties there are other methods for measuring hardness, e.g. Shore AM, Shore D, etc. The preparation of the test specimens is described in ISO 23529 or its transcription ČSN ISO 23529 [10]. This standard specifies measurement conditions relating to standard laboratory humidity and temperature. For countries in the temperate climate belt, including Central Europe, the standard laboratory temperature is defined as 23 ± 2 °C and the relative humidity as 50 ± 10 %. The standard also states that if standard laboratory conditions cannot be achieved, ambient temperature and humidity shall be used. Along with this, the standard specifies how long to temper the rubber samples in order to have the same temperature throughout the volume.

The relationship between rubber hardness and temperature has been investigated, for example, by Wehr et al. In their paper [11] is reported that the relationship is linear with a negative slope of about −0.26. At the same time, the paper shows that the relationship does not change with age, only the curve shifts by a certain value. This is consistent with the statement of Ho et al. [7] of a change in hardness of 0.6 Shore A per month.

This paper describes the possibility of determining and applying a general curve for the dependence of tyre hardness on temperature. With this general curve,

Sample	Manufacturer	Product identification	Index	Age at the measurement	Tread depth	Note
S1	Continental	PremiumContact 7	205/55 R16 91 V	0,4-0,8 years	7,9 mm	Abrased
S2	Continental	PremiumContact 7	205/55 R16 91 V	0,4-0,8 years	8 mm	Non-abrased
S3	Continental	PremiumContact 2	215/55 R18 95 H	16,9 years	4 mm	
S4	Barum	Brillantis	165/80 R14 85 T	17,8 years	3 mm	
S5	Dunlop	SportMAXX	225/45 R17 91 W	6,4 years	5 mm	

Table 1. Measured samples and their parameters.

it would be possible to calculate hardnesses to different temperatures based on a single accurate measurement. For example, this method could help determine the level of tyre degradation during vehicle inspections for accident analysis when the vehicle cannot be tested on road.

2. Materials and methods

This chapter will describe the measured samples, the measuring equipment and the process of measuring and evaluating the measured data.

2.1. Samples

Samples from summer tyres of different manufacturers and ages were used to investigate the dependence of material hardness on temperature. The size of the samples was at least 5 × 5 cm. A list of these is given below:

- Samples 1 and 2 were taken from the new Continental PremiumContact 7 tyre of size 205/55 R16 with load index 91 and speed index V. According to the DOT code, the tyre was manufactured in the 9th week of 2023, so during the measurement process its age can be determined to 0.4–0.8 years. For engineering reasons, the tyre surface is treated with a thin layer of protective coating. In order to eliminate the possible influence of the hardness values by this coating, sample 1 was abraded to a depth of 0.1 mm over the entire tread area. Sample 2 was not abraded and still contains a protective layer.
- Sample 3 was taken from a Continental PremiumContact 2 tyre of size 215/55 R18 with a load index of 95 and a speed index of H. According to the DOT code, the tyre was manufactured in the 9th week of 2006, so its age can be determined to be 16.9 years during the measurement. This tyre has not been operated for at least the last 3 years and has been stored at a constant temperature and humidity, thus slowing down the degradation process. The tyre's further history of use is unknown, as is the way it has been stored in the past. The tread depth of this tyre was 4 mm.
- Sample 4 was taken from a Barum Brillantis tyre of size 165/80 R14 with a load index of 85 and a speed index of T. According to the DOT code, the tyre was manufactured in the 14th week of 2005, so its age can be determined to be 17.8 years during the measurement. This tyre has not been operated for at least the last 3 years and has been stored at a constant temperature and humidity, thus slowing down the degradation process. The tyre's further history of use is unknown, as is the way it has been stored in the past. The tread depth of this tyre was 3 mm.
- Sample 5 was then taken from a Dunlop SportMAXX tyre of size 225/45 R17 with a load index of 91 and a speed index of W. According to the DOT code, the tyre was manufactured in week 40 of 2016, so its age can be determined to be 6.4 years during the measurement. This tyre has not been operated for the last 3 years and has been stored at a constant temperature and humidity, thus slowing down the degradation process. The tyre's further history of use is unknown, as is the way it has been stored in the past. The tread depth of this tyre was 5 mm.

The samples included tyres from different manufacturers and different ages. Extremes are also included among the ages, which could be an indicator of the influence of age on the studied relationship. For clarity, Table 1 describing each sample is provided:

2.2. Measurement and evaluation process

For hardness measurement, the HPE III equipment was used in Shore A hardness measurement modification as required by the standard. The device can measure both the hardness and temperature of the sample, as well as the relative humidity and ambient temperature. The device was calibrated with a certificate according to DIN EN ISO/IEC 17025:2018. This process is aimed at control measuring distance by using a control ring with base plate simulating a constant hardness value, in our case always 40 Shore A. Although the manufacturer declares that the device is designed to measure the hardness of the sample between 0 °C and 70 °C, measurements were made outside this range. This limitation must be taken into consideration in the evaluation of the measurement results.

The hardness of the samples was measured at room temperature and relative humidity. To measure the hardness of the samples at temperatures below room temperature, the samples were tempered to −20 °C and the measurements were performed continuously while they were heated. Similarly, the hardness of the

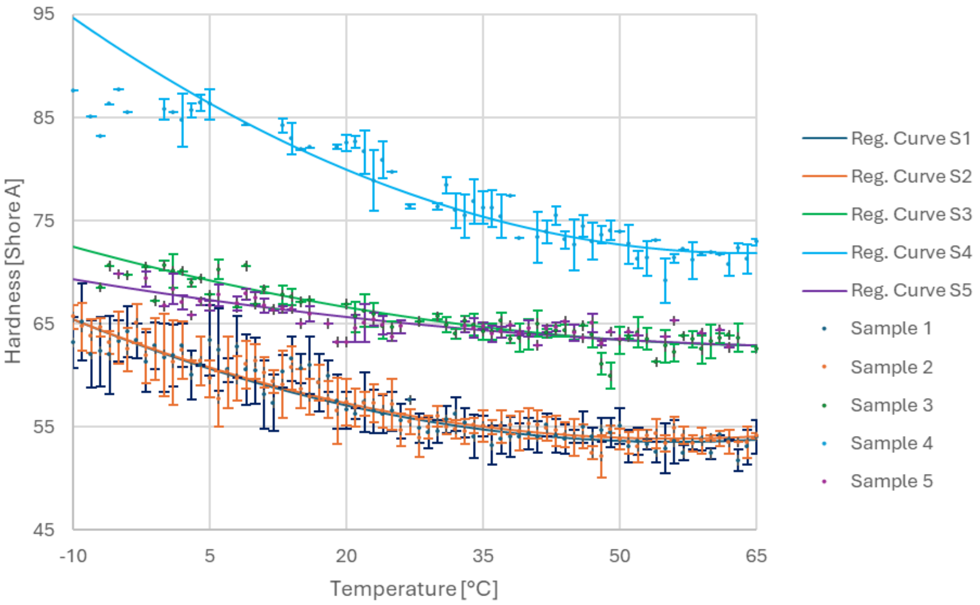

Figure 1. Temperature dependence of sample hardness with standard deviation and regression curve.

samples was measured at temperatures above room temperature by tempering the samples to 70 °C and measuring the hardness as the samples cooled. From the measured values of all 5 samples, a database of more than 1 800 temperature-dependent hardness values was recorded together with the relative humidity and ambient temperature. It was an effort to make multiple measurements for a given temperature so that any measurement error could be eliminated and the standard deviation σ in the measured values determined.

Statgraphics software version 15.1.02 was used to create the regression model. For the regression analysis, the average values of the measured hardness and temperature of the samples at the time of measurement were given as input values. The standard deviation was then used as a weight $w_i = 1/(\sigma_i^2)$ to ensure greater reliability of the regression model. Statistical significance indices representing the P-value in the ANOVA table, and the highest achievable R^2 reliability values were compared for evaluation.

3. Results

3.1. Tyre hardness vs. temperature

Statistical evaluation shows that for all samples the P-value in the ANOVA table is less than 0.05, and thus there is a statistically significant relationship between sample temperature and hardness at the 95 % confidence level. The regression curves for all samples show a polynomial function with a 2^{nd} order polynomial. Except for sample 4, the P-value for the 3^{rd} order is greater than 0.05 and thus this order is not statistically significant at the 95 % higher confidence level. The common feature for all samples is the convexity of the function and the negative slope of the curve. The graph below shows the measured values along with the standard deviation and the intercept of the regression curve for each sample.

Figure 1 shows that the dependence of hardness on temperature varies from sample to sample. For this reason, the change in hardness due to material degradation should always be considered for a new tyre of the same model and manufacturer. The possibility of using universal dependence will be discussed in the following chapter. A common indicator is the increased stability of hardness at the higher temperatures at which summer tyres are usually operated and to which they may be heated as a result of their use.

Table 2 shows the equations of the regression curves for each measured sample, where $H(T)$ is the hardness of the rubber material of the sample in Shore A units and T is the temperature of the sample in °C. In addition, the table includes the coefficient of determination R^2, the standard error of estimate σ_{est} and the mean absolute error MAE.

3.2. Determination of the average curve

From the regression curves, it is possible to identify one average curve AVG Curve that would describe the temperature dependence of the hardness of any summer tyre. Using this curve, a recalculation of the hardness and an assessment of the degradation rate could then be made even if the tyre hardness was not measured at the same temperature.

From the available regression curves of the individual samples, it is possible to determine by arithmetic averaging the coefficient a (determining the degree of curvature) and the coefficient b (determining the slope) of the average polynomial curve of the second line, which describes the dependence of the hardness of the material on temperature. The constant c, which

No. of Sample	**Equation of the Regression Curve**	**R^2 value**	**σ_{est}**	**MAE**
S1	$H(T) = 0.0027\,T^2 - 0.3061\,T + 62.1320$	99.67 %	0.7283	0.5317
S2	$H(T) = 0.0026\,T^2 - 0.2966\,T + 62.1606$	94.90 %	0.6324	0.4333
S3	$H(T) = 0.0015\,T^2 - 0.2110\,T + 70.1874$	92.69 %	1.1202	0.8143
S4	$H(T) = 0.0041\,T^2 - 0.5306\,T + 88.9063$	97.20 %	2.2211	1.4130
S5	$H(T) = 0.0008\,T^2 - 0.1296\,T + 67.9092$	86.02 %	1.2935	0.8892

TABLE 2. Regression curve equations for each sample.

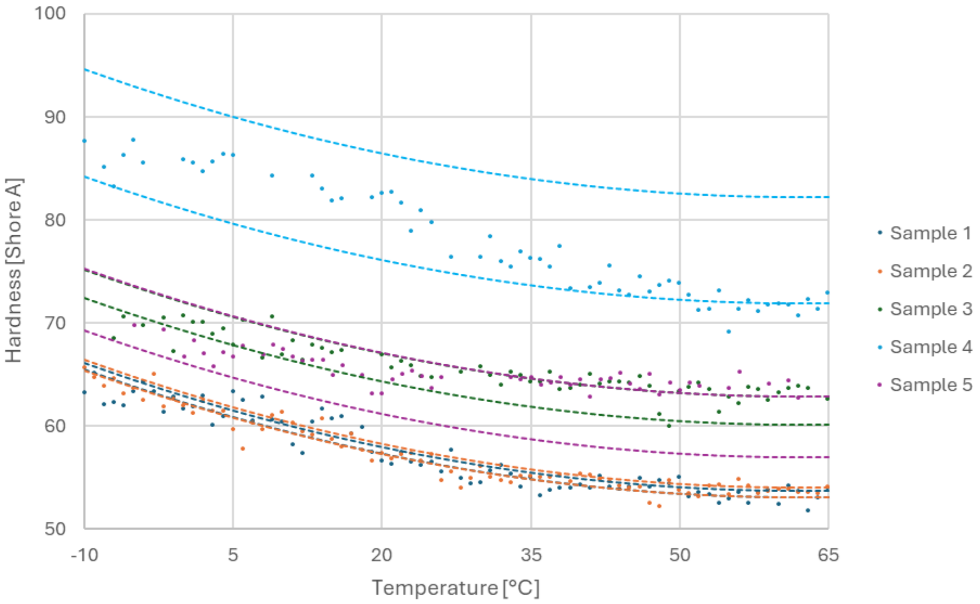

FIGURE 2. Range of AVG Curve application to samples.

indicates the shift of the curve in the hardness axis, must be calculated for each sample. As from the studies of Ho et al. and Wehr et al. [7, 11] show, this constant depends, among other things, on the condition of the rubber material of the sample.

$$H(T) = 0.0024\,T^2 - 0.2948\,T + c \tag{1}$$

Whether this equation can be used to predict the hardness at a certain temperature for summer tyres will be discussed in the following section.

3.3. APPLICATION OF THE AVERAGE CURVE TO SAMPLES

The measured hardness values for individual samples can be used to verify the average curve applied to real data. Since hardness values were not found for all samples for all temperatures, the constant c will always be determined using regression curves. In this way, the variation of the measured hardness values that gave rise to the regression curves will be included in the results.

Figure 2 shows the measured values for each sample. The dashed lines then show the ranges in which the AVG Curve (1) varies depending on the calculation of the constant c.

The range shows that the resulting AVG Curve does not adequately describe all the measured data. At the same time, the level of confidence is dependent on the value of the constant c. Respectively, whether the hardness value for a specific temperature, from which the constant c is calculated, is close to the AVG Curve.

To evaluate the reliability of the AVG Curve applied to the sample hardness data, the Average Residual Standard Error RSE calculation method was chosen. This method is used to describe the difference in standard deviations of the observed values compared to the predicted values. It is a measure of goodness of fit that can be used to analyze how well a set of data points fits the real model. The calculation of the RSE was performed by calculating the difference between the value determined by the AVG Curve and the measured sample hardness. The RSE was divided by the average value of the measured hardness of each sample to convert to a percentage value. This gives an estimate of the error relative to the average hardness value achieved by the sample over the specified temperature range. Figure 3 shows the percentage RSE between the AVG Curve and the measured hardness values of the samples.

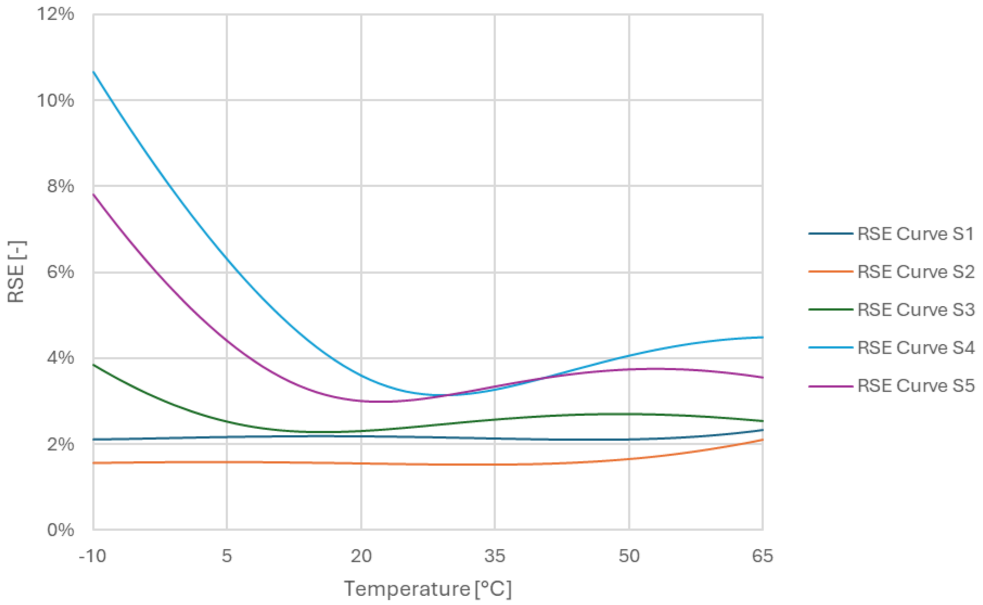

Figure 3. RSE fitted AVG Curve to samples.

The results show that for samples S1 and S2, the error using the AVG Curve is within 2 % of the average value of the measured hardness, independently of the temperature range over which the constant c was determined. Lower error values can be observed for samples S1, S2 and S3, which are samples from the same tyre manufacturer. For the other samples, the error increases when using the calculation of the constant c at low temperatures. For this case, high inaccuracy is inserted into the resulting hardness recalculation when using AVG Curve. The 4 % error limit corresponds to 2–3 Shore A units for the measured samples, which for example corresponds to up to 5 months of different tyre age when using the Ho at al. calculation [7]. At the same time, due to the stabilization of hardness at higher temperatures, even a 2 % error can significantly affect the results.

4. Discussion

The results presented in this paper show that although the dependence of rubber hardness on temperature may appear linear over a limited temperature range, it is more accurate to use a 2^{nd} order polynomial curve when considering a larger range. In this paper, tyre hardness was not investigated at extremely low or extremely high temperatures, which could change the hardness beyond the investigated dependence. Although the manufacturer of the measuring device states that the device is not designed to measure sample hardness below 0 °C, the results of the regression analysis show good agreement in the measured data even below this critical temperature. Only for sample S4 the regression curve does not agree significantly with the measured data.

The AVG Curve reliability results indicate that there is increased inaccuracy at low temperatures for samples S3, S4 and S5. This inaccuracy is not limited by the 0 °C. Rather, it will be due to the lower number of measurements for these samples at low temperatures, and therefore the lower weight wi used in the development of the regression curves for these samples.

Due to the different chemical compositions of tyres from different manufacturers or model series, it is not possible to establish a curve describing the general range of summer tyres that would perfectly describe the temperature dependence of hardness. Using the AVG Curve produces an error which is dependent on the calculation of the constant c. For this reason, it seems appropriate to compare the hardness change at a specific temperature within the material degradation for tyres of the same material or chemical composition.

For sample S4, where the highest hardness was measured, the question arises whether the wear caused the exposure of another than the thread layer. The measured surface may not necessarily be homogeneous. This layer may have different chemical composition and mechanical properties. To identify this layer, a material analysis could be carried out using Computer Tomography. However, this was not performed as part of the study.

Additional measurements involving a larger number of samples would be appropriate to verify the results presented in this article. In addition, further measurements could be extended to winter tyres.

5. Conclusions

This article was aimed at the possibility of recalculating the tyre hardness for different temperatures using the established average curve of hardness versus tyre temperature. The results show that the use of an average curve is associated with an error that can significantly affect the resulting hardness value found. The resulting error can be reduced by using tyres of the same model and manufacturer.

The regression curves for all samples show a polynomial function with a 2nd order polynomial for the temperature range $-10\,°\mathrm{C}$ to $65\,°\mathrm{C}$. For each of the samples measured, the regression curve varies the coefficient a (determining the degree of curvature) and the coefficient b (determining the slope) of the polynomial curve equation. The constant c of the polynomial curve equation must always be calculated for a specific sample based on the known hardness of the sample at a known temperature.

The results of the temperature dependence of summer tyre hardness show that hardness stabilises as temperature increase. Samples S1, S2, S3 and S5 consistently show that in the temperature range 30–65 °C the hardness change is minimal. On the other hand, at low temperatures there is a significant increase in hardness, indicating that the change in mechanic properties may also affect the performance of summer tyres at these low temperatures.

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