Nonlinear modelling speeds up tyre rubber recipe development

Introduction

Readers of this magazine have read about nonlinear modelling [1-3] so the basics are not repeated here. Nonlinear modelling helps speed up materials and process development in several industrial sectors, and is particularly useful for plastics and rubbers, since their behaviour tends to be relatively complicated. Here we have a glaring example.

Automobile tyres are made of several rubber recipes. Tyres for different purposes and different road conditions and climates need different properties. Different parts of the tyres require different material properties, and they are achieved by compounding rubbers in different proportions, besides using a number of additives in different amounts. Several material properties are of interest to tyre manufacturers. The rubber mix before vulcanisation needs to have viscosity within certain limits. After vulcanisation, hardness, tensile modulus, tensile strength, tear strength, elongation at break, dynamic mechanical properties, wear resistance, etc. are of interest. To achieve a desired combination of several of these properties is no easy task. Trial and error experiments are often carried out in large numbers for developing rubber recipes which lead to a desired combination of several of these properties.

Why nonlinear modelling

When we have reliable mathematical models to predict these properties, the experimentation requirement reduces by a large fraction. The models can simulate experiments in seconds instead of laboratory work of hours or days. However, the relations between the composition variables and the material properties are fairly complicated. Conventional empirical modelling techniques are linear and cannot describe these relations well. New techniques of nonlinear modelling, however, are very efficient for relating material properties with composition variables. Often process variables and dimension variables are also taken into account.

Experimentation

In the recent work of Nokian Tyres, a total of 43 experiments were carried out with different recipes. A much smaller number would have been sufficient for this work, and the original experiment plan had only 28 experiments. The experiments were planned such that sufficient information on nonlinearities can be extracted from the experimental data. Several material properties were measured from the samples produced in the experiments. From the raw data set, it was possible to see some effects of certain composition variables. Figure 1 shows the effect of silica on viscosity (scale on the left) and tensile strength (scale on the right). The fractions of natural rubber, styrene butadiene rubber and butadiene rubber are the same for all these points on the plot. Needless to say, the effects of silica on viscosity and tensile strength are not very linear.

The raw experimental data was then analysed and pre-processed, after which nonlinear models were developed and tested for several material properties over a period of a few months using the NLS 020 software. The experimental data taken into use was consistent and of very good quality, and as a consequence, excellent nonlinear models could be developed. The correlation coefficients of all the models were well above 90% and for some properties like viscosity, they were above 99%. It is natural that the nonlinear models perform very well since the effects are not very linear, while the linear models will not even hesitate to predict negative values of material properties. Figure 2 shows a plot of measured values of hardness against the values predicted by the nonlinear model on the vertical axis.

Using the nonlinear models

Once the models are ready, they can be used for several purposes with appropriate software like LUMET systems. Besides being able to predict the values of the material properties, one would like to see the effects of different ingredients on the properties. These effects need not be simple, like just increasing or decreasing. There can be a minimum in the curve, as seen from Figure 3, and the curves might change their form if the amount of some other ingredient changes. In Figure 3, elongation at break is plotted against natural rubber content for different values of sulphur content.

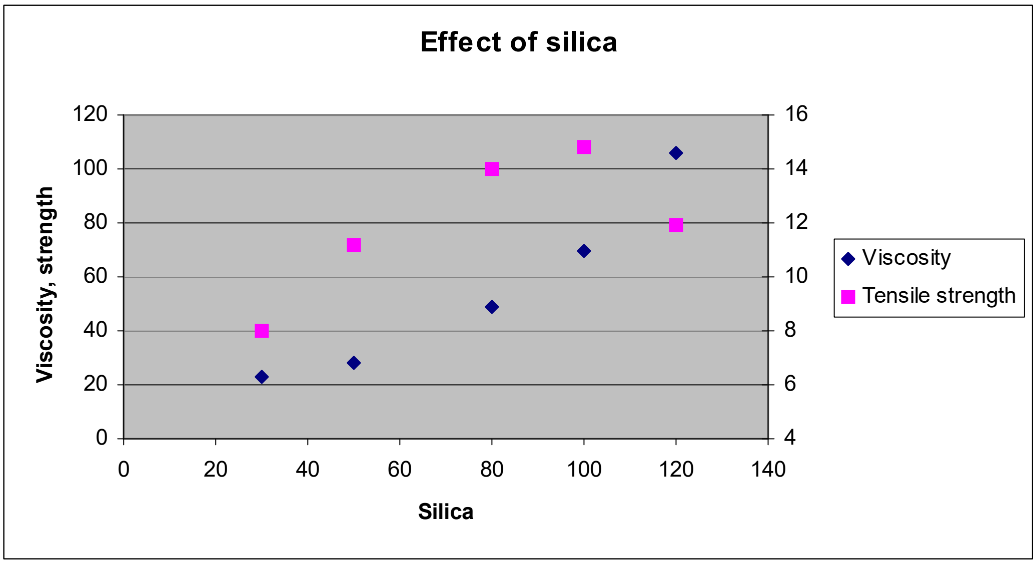

Figure 1. Effect of silica on viscosity (scale on the left) and tensile strength (scale on the right) as seen from the raw experimental data

Figure 2. Measured values of hardness against the values predicted by the nonlinear model on the vertical axis

These rubber recipes were essentially ternary mixes – containing three rubbers, besides additives. Thus their compositions can be depicted on ternary diagrams. Figure 4 shows the contours of viscosity on a ternary diagram, with viscosity predicted by a nonlinear model. On this plot, the amount of silica, sulphur, etc. are kept constant. The highest value is at 100% SBR, the top of the triangle, while the lowest value is at 100% natural rubber on the right extreme of the triangle.

Conclusions

In many industrial sectors including automobile tyres, better materials give a competitive edge in the market. Nonlinear models save time, effort and money in materials development, often quite drastically. Nonlinear models are a lot more capable of describing complicated relations than linear statistical techniques because nothing in materials science or process engineering is very linear. With appropriate mathematical tools, these models can be used very efficiently to determine good recipes.

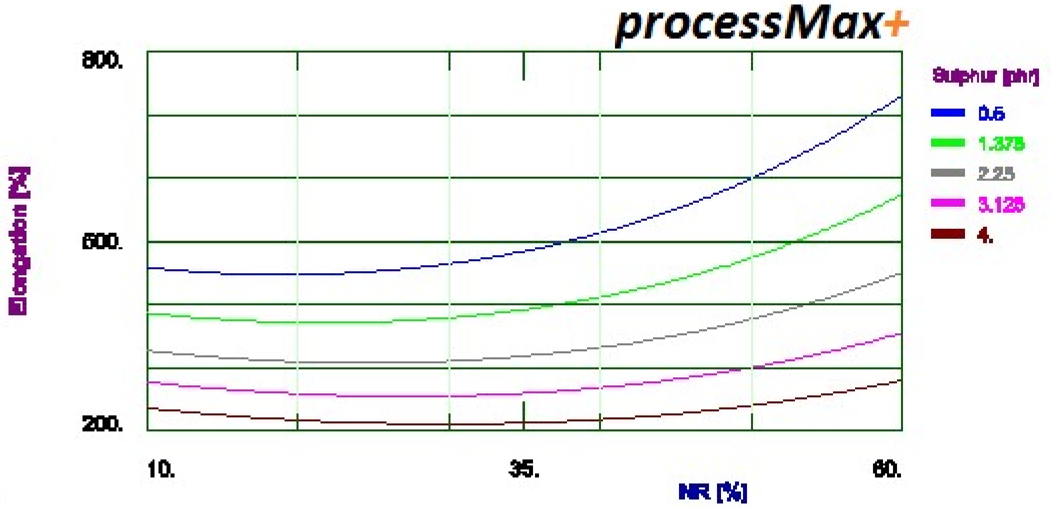

Figure 3. Effect of natural rubber content on elongation at break for different amounts of sulphur

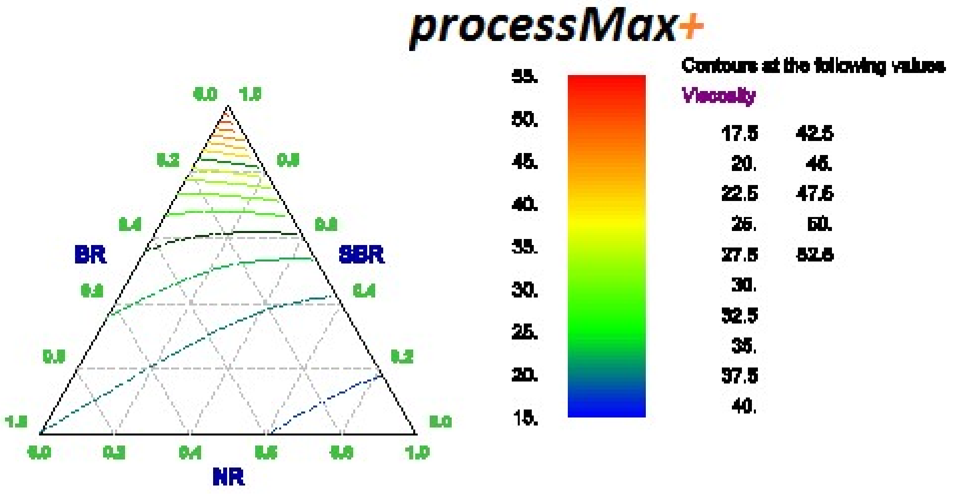

Figure 4. A ternary diagram showing contours of viscosity