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Budapest University of Technology and Economics
Faculty of Civil Engineering
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Thesis Booklet

Stiffness of Asphalt Mixtures in Function of Loading Time, Temperature and Particle Size Distribution

PhD Dissertation
for open discussion

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I. OBJECTIVE OF THE DISSERTATION

Primary objective of the dissertation was to examine the effect of temperature and loading time on the stiffness of asphalt mixtures.

The Hungarian experts of the profession already regarded stiffness as one of the essential characteristics of the asphalt mixtures. This view was further strengthened both by the recent use of high modulus asphalt mixtures in Hungary and the Hungarian technical specifications' preference for the fundamental tests. What further increases the high importance of the matters concerning stiffness is the escalating research efforts made recently in Hungary in respect of the mechanistic pavement design .

Currently, however, to determine the stiffness of the asphalt, a single parameter is used, which is valid only at a specific temperature. For this reason, my efforts were focusing on finding a different form of analysis of the results of stiffness tests carried out at changing temperatures and various loads. Having reviewed the international literature, it became obvious that once the earlier concerns are clarified and if one relies on the achievements of information technology, the application of the Time Temperature Superposition Principle, known in the area of rheology, can be an efficient tool for studying the behaviour of asphalt mixtures.

I based my exploration on this principle, and first I examined how the complex modulus can be determined in a specific frequency range for a Hungarian asphalt mixture. Then I studied how the stiffness data, which is more comfortable for the professionals to use, could be processed by using a master curve. Also, I examined how such data could be forecasted.

II. SHORT DESCRIPTION OF THE RESEARCH WORK

With regard to the structure of my dissertation, I tried to ensure that each chapter would be interpretable in itself. In terms of structure, each chapter starts with the theoretical background of the examined topic and is supplemented with international references, if applicable. Then the second part of every chapter discusses my own findings followed by a short summary at the end of the chapter.

The dissertation includes 5 main chapters.

Chapter 1 is the introduction followed by Chapter 2 discussing the basic mechanical engineering, mainly rheological, knowledge base that I relied on during my research work. Using the above information as a basis, I employed the test results of certain Hungarian asphalt mixture tests to describe the so called Huet-Sayegh model, which provides not only a better prediction of stiffness than the traditional rheological models do, but also helps illustrate the behaviour of an asphalt mixture in function of time as well as frequency. This model allows a more sophisticated analysis of the differences of asphalt mixtures, while it also facilitates the illustration and analysis of all test results of varying temperatures and loadings in a single framework. By using this model, it is possible to provide a highly accurate estimation of the complex modulus for various loading frequencies outside of the testing range.

The first part of Chapter 3 includes the fundamentals of the Time Temperature Superposition Principle as well as the possible alternatives for determining the shift parameters. In the second part of this Chapter I relied on the results of Hungarian asphalt mixture tests to describe a possible way of creating a master curve with the support of the so called sigmoid model. To the extent of the data that I had at my disposal, I used the master curve to examine the predictability of material stiffness for temperature ranges that were outside of the scope of the tests and also analysed the reliability of such predictions. The master curve method provides a unique identifier for the asphalt mixture that may become the basis of quality assurance systems for the production and application of asphalt mixtures.

The results of my research into the calculation-based identification of asphalt mixture stiffness are included in Chapter 4. To begin with, several models that are also well-known in Hungary are described, starting with the earliest ones up to the recently developed Hirsch model. In the second part of this Chapter I used the Witczak model to compare the accuracy of stiffness estimations for various mixtures first with the measured values and then with the estimations provided by the Shell Bands software.

It would be highly beneficial to have some preliminary information of the mixtures' stiffness available already in the design phase of such mixtures in order to be able to produce cost efficient, yet well performing mixtures. Taking the fact into account that no other model but the Witczak correlation uses particle distribution parameters along with other data to estimate stiffness, a large number of laboratory data were used in Chapter 5 to verify the accuracy level of the Witczak model for determining the stiffness of mixtures with varying particle size distribution and bitumen contents.

Theuse of the Witczak predictive model for stiffness also provided an opportunity to use the input data as random variables to examine stiffness as a stochastic feature. Monte Carlo Simulation technique was applied to simulate the frequency bar chart for stiffness, which has proven that the expected stiffness is not just a determined value, but it can also be used for a more thorough analysis of performance changes at the asphalt mixture plants.

There is a short summary at the end of the dissertation.

III. THESES

THESIS 1

Using Hungarian asphalt samples, I proved that if facilitated by the Huet-Sayegh model, a highly accurate description of the loading time- and temperature-dependent behaviour of the asphalt mixtures be provided. This allows the direct comparison of the results asphalt mixture tests carried out at different frequencies and temperatures. Also, this helps study such frequency ranges that are impossible or difficult to apply under experimental conditions.

(16)

I used Hungarian asphalt samples to test the accuracy of the Huet-Sayegh model. For the optimization, I used the Solver module of the Excel software . The results (figure 1) properly match the measured values, i.e., the determination coefficient (R^2) for the measured and estimated stiffness values and the phase angles are always above 0.98. This strong correlation is a real achievement, especially for the phase angles, because other models of this kind (for example the Burgers or the general Maxwell or Kelvin models) are unable to provide such a high level of accuracy.

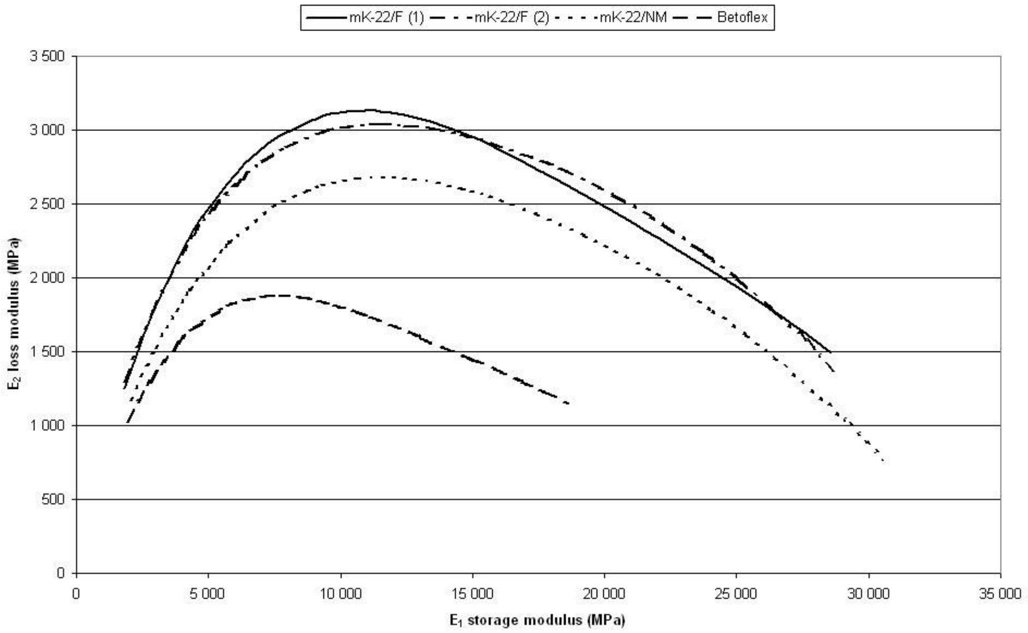

Figure 1: Graph of the Huet-Sayegh model's results

Recording the full temperature scale related physical behaviour of asphalt mixtures is essential for some applications, for example, the pavement design softwares , because the models can help create an algorithm among parameters such as loading frequency, stiffness, phase angle and temperature.

In addition to my exact mathematical description of the measurement results, I also examined how accurate the results of the model's output data can be for the range outside the test regime.

For this purpose, a Cole-Cole diagram was created for the stiffness values measured at 3 and 10 Hz loading frequency, and I developed a prediction for the 1 and 30 Hz on the basis of the data thus gained.

Figure 2 shows the Huet-Sayegh model's Cole-Cole diagram, where the values are measured at 1 and 30 Hz for a specific mixture at a specific temperature and it also shows the predicted stiffness values for the same load levels.

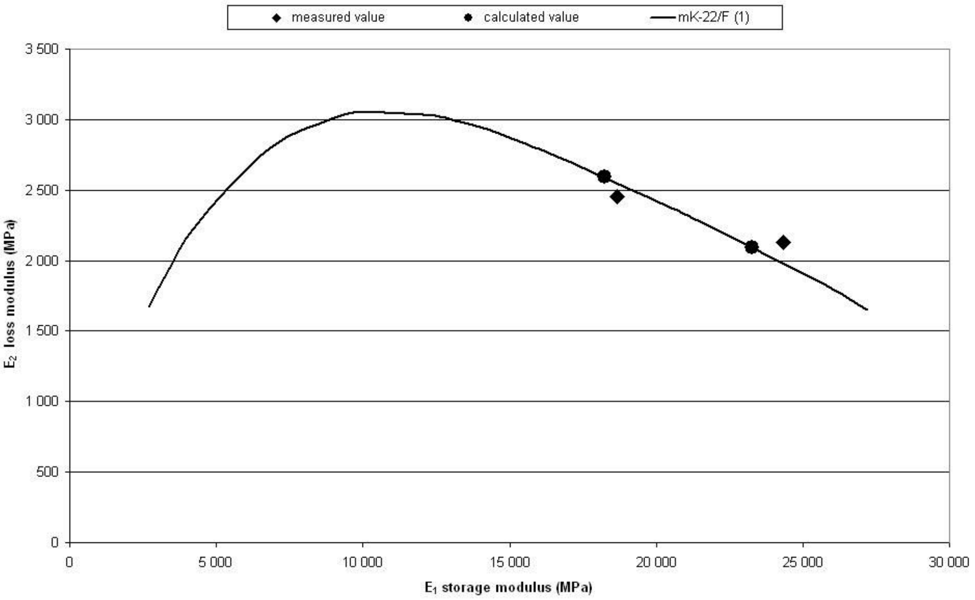

Figure 2: Comparison of measured values with the model's output data

Having completed the calculations and the measurements in the temperature range of -10 to 30°C, I proved that the model remains accurate and continues to provide reliable forecast also for the frequency range outside of tested range even when the number of the test samples is reduced.

THESIS 2

Using Hungarian asphalt samples, I proved that if facilitated by the Sigmoid model, a highly accurate description of the load time- and temperature-dependent behaviour of the asphalt mixtures can be provided. This allows the direct comparison of the results asphalt mixture tests carried out at different frequencies and temperatures. Also, this helps study such temperature ranges that are impossible or difficult to create under experimental conditions.
(2), (3), (18)

The similarity of the temperature modulus graph and the time modulus graph may suggest that both temperature and time can create the same kind of rheological changes that allows for the interconversion of the two volumes. This conversion is realised through the creation of the so called master curve.

I used the Arrhenius shift parameter to create the master curves for the tested mixtures. Then I placed a sigmoid shaped function on (1) the resulting plot.

$$log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta-\gamma log f_r}} \tag{1}$$

Where

E* = complex modulus (MPa)
α, β, δ, γ = typical constant parameters of the mixture
f_r = reduced frequency (Hz)

Figure 3 shows the master curves for different mixtures. These master curves allow the collective handling of the measured isotherms and the complex comparison of the mixtures.

In connection with the master curves, I also examined the accuracy level of the predictions for the stiffness values of non-tested temperatures. To create the master curves, I reduced the number of isotherms and used those stiffness values of the tested mixtures that were measured at temperatures of 0, 10, 15 and 20 °C. The resulting master curves, however, may also be expanded to various other temperature ranges, as shown in Figure 4. I examined the correlation between the set of estimated stiffness values with temperatures from -10 to +30 °C and the set of measured values, and proved that the master curve is a tool to create accurate stiffness predictions in respect of both the lower and medium temperature range for all four tested loading levels.

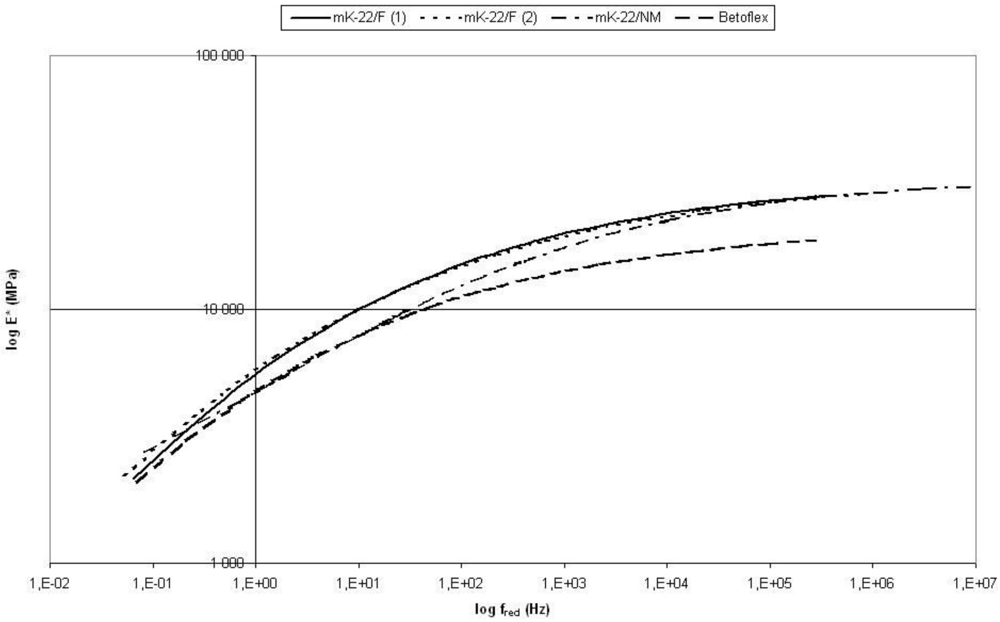

Figure 3: Master curves of different asphalt mixtures

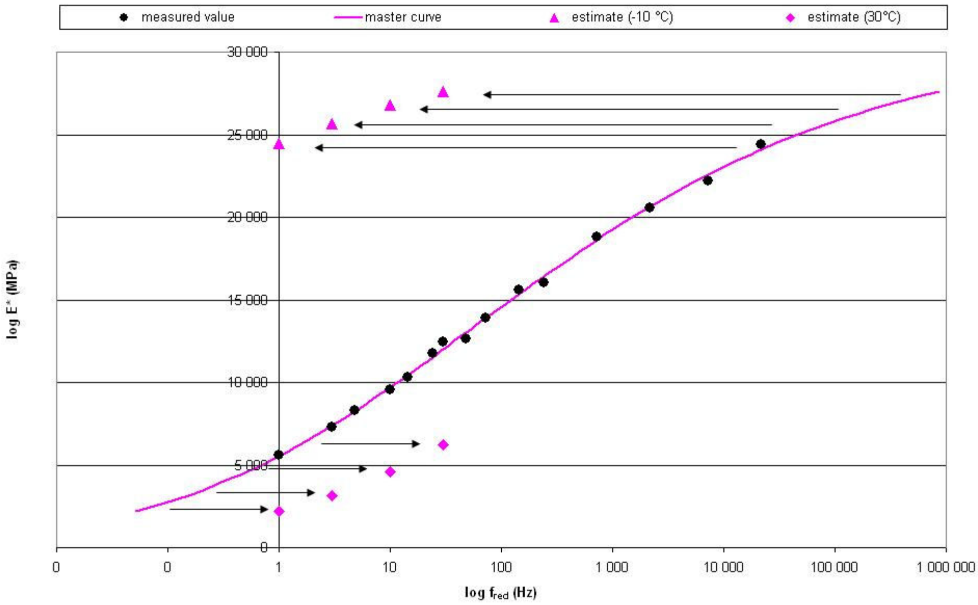

Figure 4: Master curve facilitated estimation of stiffness values for untested temperature ranges

THESIS 3

I examined the Witczak predictive model for stiffness and proved that the model's accuracy is at least the same or better than the prediction formulas currently employed in Hungary.

(20)

There is a need for faster and simpler procedures in addition to the time consuming and resource intensive laboratory tests to determine stiffness profiles. For this purpose, I used the Witczak model, which is less known and has rarely been used in Hungary, to determine the accuracy level of the model for mixture stiffness.

I made calculations involving several Hungarian asphalt mixtures, and compared the results with both measured values and Shell Bands-based predictive values (Figure 5).

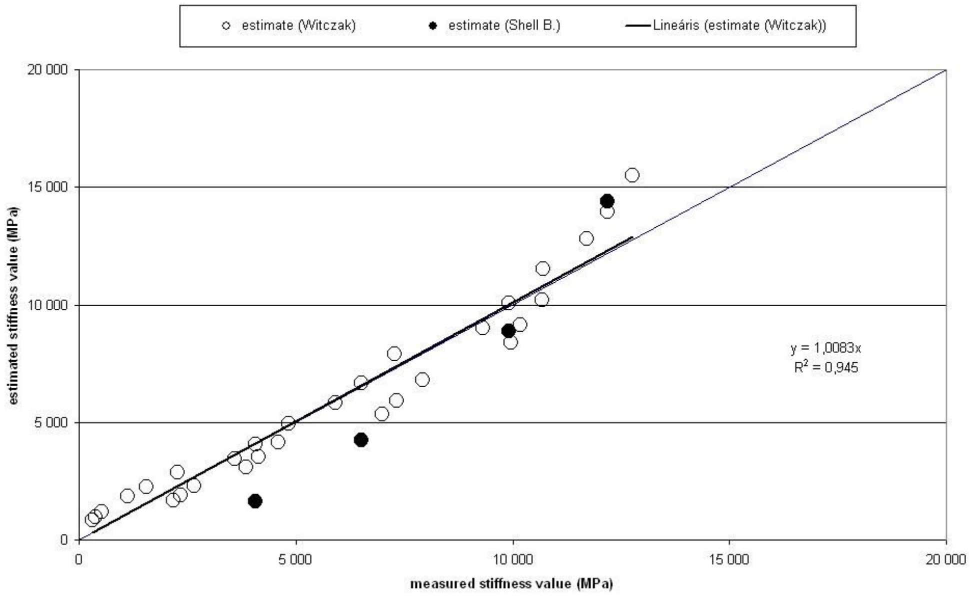

Figure 5: Comparison of measured values with the model's output data

The determination coefficients (R2) between the measured and estimated values were ranging from 0.89 to 0.96 for the tested four mixtures. The results confirmed that in respect of the mixtures I had tested, the Witczak predictive model's accuracy is at least the same or better than the Shell Bands formula, which is widely employed in Hungary.

THESIS 4

I carried out a series of tests and demonstrated that by changing the run-up target time of the IT-CY test, frequency load can be simulated and that the resulting data is in strong correlation with the predicted values of the Witczak predictive model of stiffness.

(2), (20)

I determined the stiffness of the asphalt mixture with the IT-CY (indirect tensile) and 2PB-TR (2 point trapezoid bending) methods at different temperatures, and proved that a very strong relation is present between the run-up times and the tested frequency values. (Figure 6)

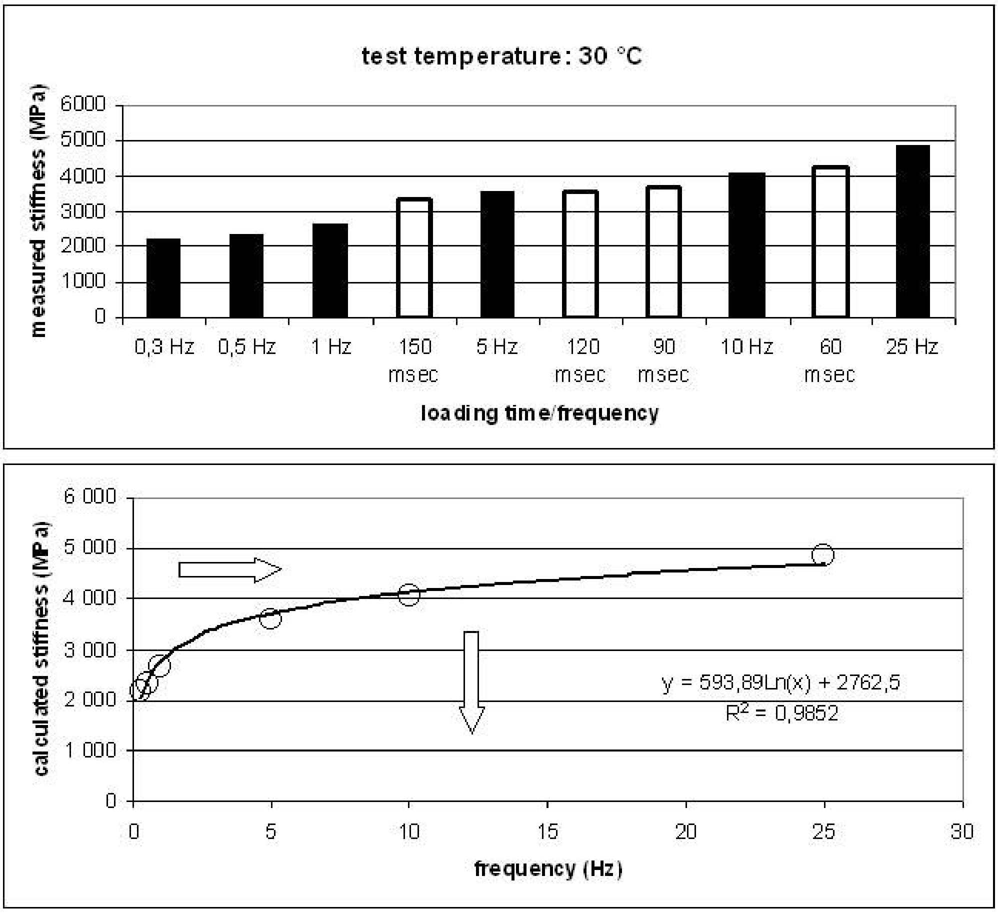

Figure 6: Relation of the run-up time and the load frequency

This helped me to define a conversion factor for each test temperature that allowed me to associate each of the different run-up target times of the IT-CY tests with a corresponding load frequency.

Applying this procedure gave me the opportunity to examine the accuracy of the Witczak model by involving the stiffness test results of a large number of tests carried out on three different mixtures. Four temperature levels and four load levels were used to carry out 144 tests for each mixture, i.e., the model was successfully tested against a set of 432 IT-CY stiffness test results.

I used the Shell Bands procedure as a reference to compare it with the stiffness estimation. The figures of table 1 below show for all three mixtures that the model provided more accurate results than the Shell Bands formula, which is a procedure widely employed in Hungary.

MODEL	AC 22 BINDER (F) 50/70	AC 22 BINDER (F) 10/40-65	AC 11 WEARING (F) 25/55-65
Shell Bands	28,16%	19,14%	32,24%
Witczak	12,56%	11,11%	19,12%

Table 1: Average error value of the different methods for each mixture

THESIS 5

I used the results of a large number of tests to prove that the master curves of the asphalt mixtures can be created by using the stiffness values coming from IT-CY tests that were carried out with varying run-up target times. This allows the direct comparison of asphalt mixture tests even if they were carried out with varying loads and at different temperatures.

(2), (20)

Four temperature levels and four loading levels were used to obtain the results of 432 IT-CY tests to create the corresponding master curves and to examine the effect of different particle size distribution and binder on the stiffness of the asphalt mixture.

Hence, for the purpose of the tests it was ensured that the particle size distribution for each of the three mixtures will be the same as the lower and upper limit envelop as well as the mean of these graphs as defined by the Hungarian technical standards. The analysis brought an unexpected result for all three of the mixtures: the stiffness of the mixtures tailored to the lower limit graph was always significantly weaker than the stiffness of the mixture of the other two PST. Also, there was no tangible difference between the stiffness of mixtures that were designed to match either the upper or the lower limit envelop.

The set of measured values of the mixtures with different PST also offered an opportunity for me to further analyse the Witczak predictive model in terms of how well it can predict the effect of the PST changes on the stiffness of the asphalt mixture. The analyses proved that the model provides a surprisingly accurate response to the changes of PST Another finding is that the shapes of the master curves created on the basis of estimated stiffness data are the same as those of the master curves carrying measured values.

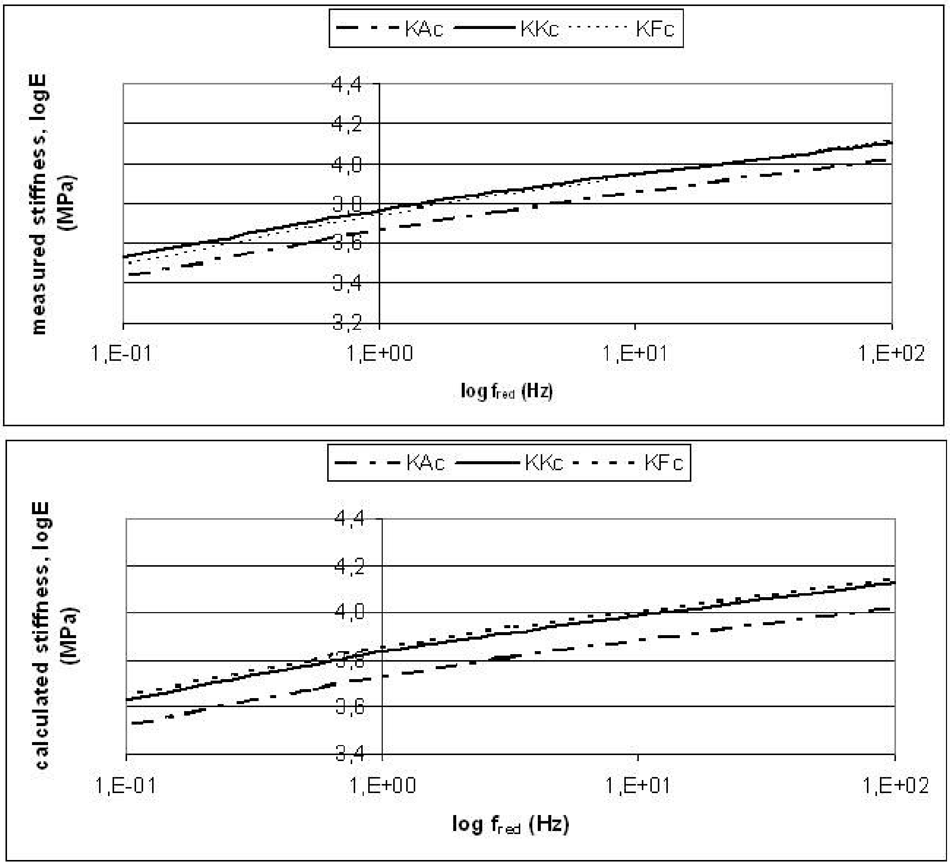

Figure 7: Comparison of master curves comprising measured stiffness values for mixtures of different PST with master curves reflecting the predicted stiffness values on the basis of the Witczak model

THESIS 6

Relying on the Monte Carlo Simulation, I proved that the stiffness of asphalt mixtures can be defined as a stochastic variable through the application of the Witczak model, which also makes this model suitable for supporting the analysis of variation in the production quality of asphalt mixtures.

(1), (20), (21)

The composition of produced asphalt mixtures may fail to meet the requirements by varying degrees. I also analysed the effect of this unavoidable production quality variation on the resilience of the finished asphalt layer.

When I used the Witczak predictive stiffness model, I treated the input data as random variables to examine stiffness as a stochastic feature. For the purpose of the simulation, I used the simulated frequency histograms, shown in Figure 8, to create a frequency chart for the stiffness of 12 mixtures. I used the Hungarian standards for PST and mixture composition to define the expected values and deviation of all input data.

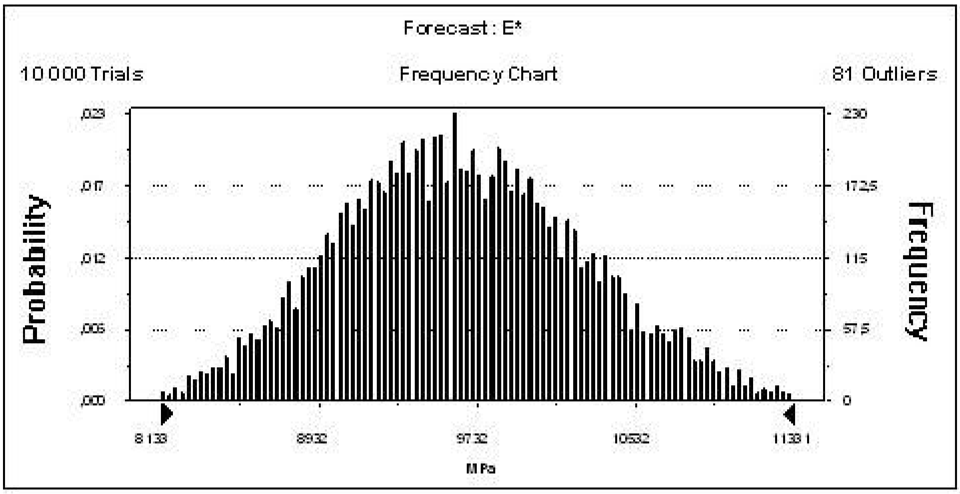

Figure 8: Simulated frequency histogram for the AC 22 mixture's stiffness

Certain tests facilitated by the Monte Carlo Simulation technique confirm the theory that the expected stiffness is not just a value determined this model, but it can also be used for a more thorough analysis of performance variation at the asphalt mixture plants.

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