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RESEARCH ARTICLE

Determination of master curves for asphalt mixtures by means of IT-CY tests[1]

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Abstract

The concept of ecologically conscious and energy saving roads must be expanded to the performance of the asphalt mixtures as well as to the test related to it. This paper investigates the tests focusing on a better description of the behaviour of asphalts as well as on a deeper revelation of the impact of different compositions. Based on the international experiences the recording of the asphalt's complex module over the entire temperature range by the determination and evaluation of the mater-curves appeared as a possible solution for more precise description of the asphalt behaviour.

Keywords

asphalt mix · master-curve · sigmoid model

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1 Introduction

Relating to the criteria for asphalt mixtures the Hungarian Technical Committees, using the opportunity of choice given by the product standard, chose the fundamental approach instead of the empirical method. This choice against the previous Hungarian practice directly valued up the tests for obtaining the behavior and performance for asphalt mixtures ([2]).

Such a measurement is e.g. the determination of one of the most important properties, the stiffness, where up till now for the evaluation of the asphalt one single value determined at one single temperature is used. This data is surely well suited for factory production control or for control tests, but it is only informational, and can not be used for the characterization of the actual behavior of the mixture, or for the determination of the differences between mixtures. For works concentrating on a deeper comprehension and evaluation of the mixture's behavior the recording of the complex module over the whole temperature spectrum is needed.

The appendix of the standard "MSZ EN 12697-26 Bituminous mixtures. Test methods for hot mix asphalt. Part 26: Stiffness." with this issue: "The stiffness modulus for the required loading time is determined on the master-curve at the required temperature." The standard approximately gives the principal of the determination of the master-curve, and an example with the results shows in Fig. 1, but does not contain any actual methods, which are needed for the determination.

In addition to the fact, that for the construction of the master-curve a variety of theoretical solutions is offered, the determination of the master-curve is based on tests with harmonic loads, performed at different frequencies, whereas the time-expenditure for the fabrication of the specimen necessary, as well as the probable inhomogeneity of the sample set high priority to the issue of a possible simplification of the tests. The present paper intents to examine, whether it is possible under Hungarian conditions to obtain the base data necessary for the creation of the master curve based on the results of indirection

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tension tests (IT-CY) on cylindrical specimen.

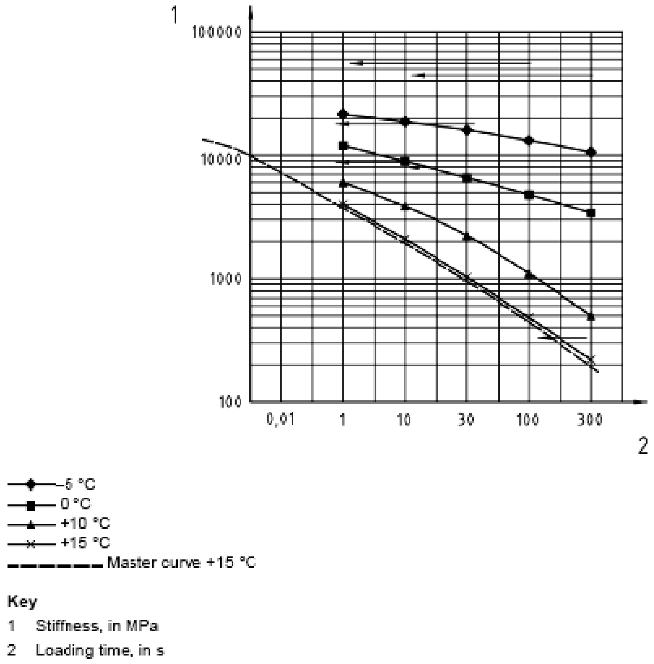

Fig. 1. Estimation of the stiffness modulus for loading times of 0.02 s at a temperature of 15˚C (Source: MSZ EN 12697-26)

For this purpose we examined, what accuracy could be reached in the simulation of the loads with different frequencies by changing the rise times defined in Fig. 2 during the IT-CY test, and whether a master-curve could be fitted on the loading time - stiffness values, which were generated this way.

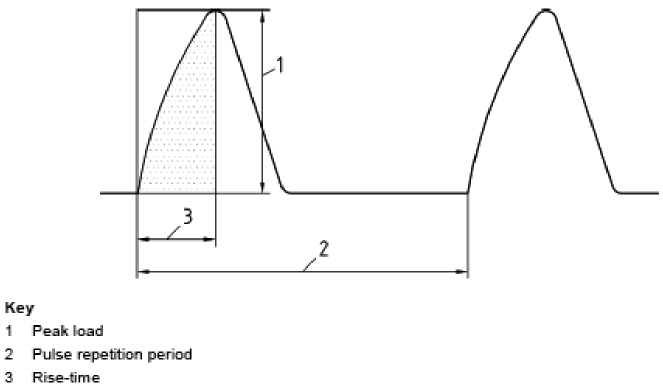

Fig. 2. Schematic illustration of the used pulsed load (Source: MSZ EN 12697-26)

2 Composition

For the validation of the assumption we planned a frequently used Hungarian mixture, with three mainly different, but still standard aggregates. The three different grain size distributions of the AC 22 (F) mixture are shown in Fig. 3.

To each grain size distribution 3 bitumen content were assigned, with 3.5–4.3-50 w% respectively.

3 Master-curve determination by means of sigmoid model

According to latest research results in case of asphalt mixes the master-curve is a continuous, none decreasing and necessarily above and below bounded function. Considering these it can be drawn as a non-linear s-shaped so called sigmoid function. The curve was approximated with the following formula (NCHRP 1-37-A, 2004):

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\,(\log(t_r))}} \quad \text{or}$$
$$\log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta-\gamma\,(\log(f_r))}} \tag{1}$$

In Eq. (1) t_r represents loading time at reference temperature, f_r is the reduced frequency, δ is the minimum value of $|E^*|$, $\delta+\alpha$ is the maximum value of $|E^*|$, and β and γ are the parameters of the sigmoid function. On Fig. 4 the graphical interpretation of the parameters is shown. Where

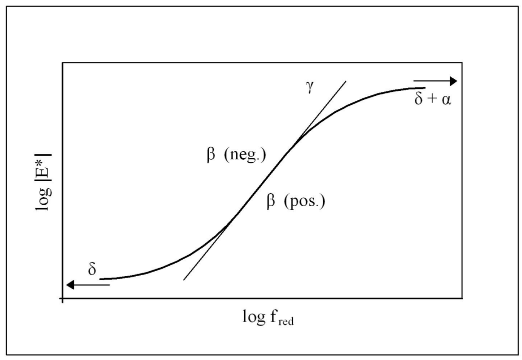

Fig. 4. Parameterization of the sigmoid function

- $|E^*|$ = the stiffness (MPa)
- δ, γ , β, α = constant parameters and
- t_r= the reduced loading time (s)
- f_r= the reduced frequency (Hz).

A fundamental issue is the determination of the t_r reduced loading time, which can be given using the shift factor as follows:

$$(t_r) = \frac{t}{a(T)} \tag{2}$$

The shift factor was determined based on the classic Arrhenius equation.

$$\log\left[a(T)\right] = \log e\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{T_{\mathrm{ref}}}\right) = C\left(\frac{1}{T}-\frac{1}{T_{\mathrm{ref}}}\right) \tag{3}$$

Where

- $a(T)$ = the shift factor
- T = the testing temperature (K)
- T_{ref} = the reference temperature (K)
- C = a constant (K)

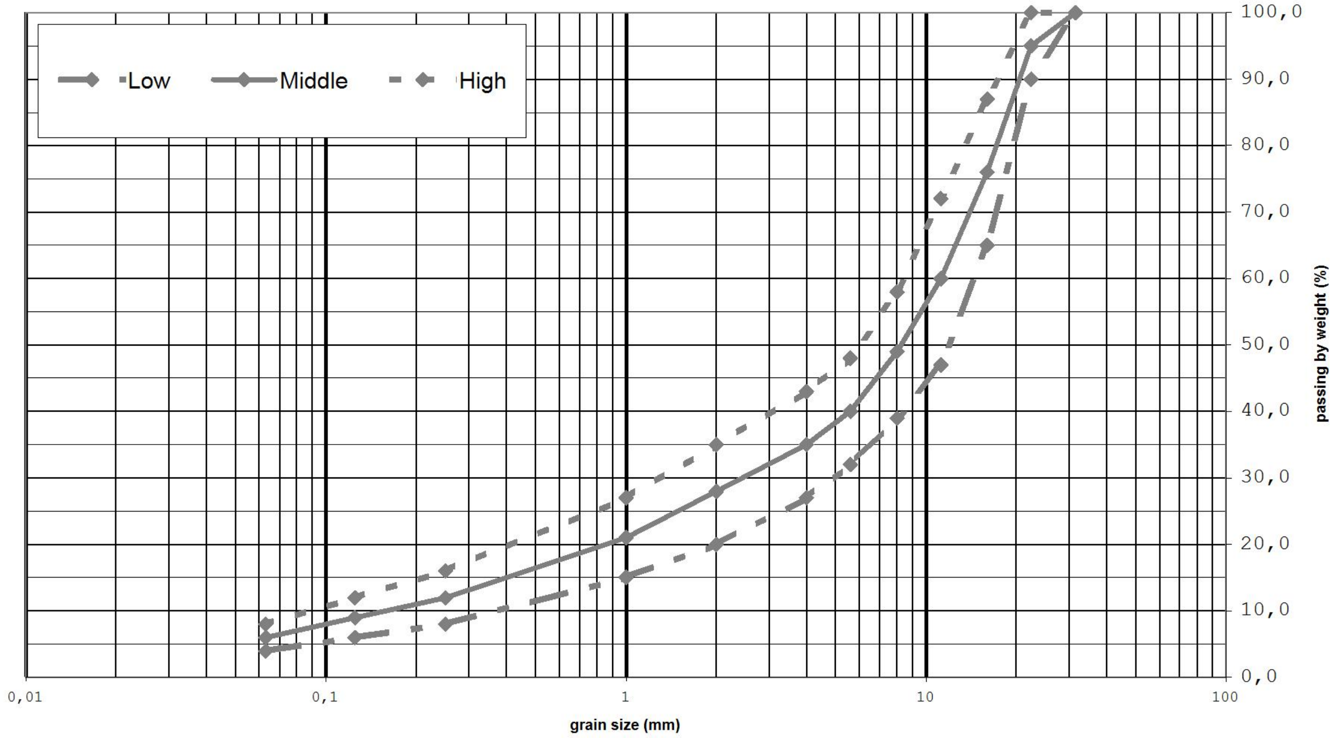

Fig. 3. The three different grain size distributions of tested mixtures

Tab. 1. The main parameters of the characteristic mixtures

Mixture code	Bitumen content weight%	Marshall density [kg/m^3]	Max. density [kg/m^3]	Void content [%]	Bitumen volume%	Rate of filling [%]
mKL1	3,5	2 397	2 617	8,38	8,27%	50
mKL2	4,3	2 418	2 580	6,26	10,24%	62
mKL3	5	2 412	2 570	6,15	11,88%	66
mKM1	3,5	2 459	2 583	4,78	8,48%	64
mKM2	4,3	2 474	2 590	4,46	10,48%	70
mKM3	5	2 466	2 558	3,56	12,15%	77
mKH1	3,5	2 433	2 621	7,20	8,39%	54
mKH2	4,3	2 472	2 575	3,99	10,47%	72
mKH3	5	2 472	2 557	3,29	12,18%	79

- ΔH = the activation energy (J/mol) and
- R = the gas constant, 8,314 J/mol K.

The parameters of the function that describes the relation between stiffness and load can be determined by the so-called simultaneous optimalization technique. The method is based on the simultaneous variation of the shift factor and the parameters α, β, γ, δ to fit the most suitable function to the measured points. This optimal value search can be relatively simply performed by the Solver module of Excel. Relating to the investigated asphalt mix the fitting of the sigmoid function was performed by using the constant (C) in Arrhelius' shift factor as an additional variable.

4 Test results

The IT-CY stiffness test were performed at temperatures of 0, 10, 20, 30°C with targeted rise times of 60, 90 120 and 150 ms. The targeted rise times could not be set in each case with full accuracy, but these deviations in principle do not influence the evaluability of the results. Table 2 shows the actual rise times for each mixture.

Tab. 2. Actual rise times

Mixture Code	Loading time (msec) (averaged over the single temperature ranges)			
mKL1	65	92	118	148
mKL2	65	89	118	150
mKL3	63	90	119	150
mKM1	68	94	123	152
mKM2	68	95	125	153
mKM3	67	92	121	150
mKH1	68	97	125	154
mKH2	67	95	123	152
mKH3	66	92	121	151

For the measurement we produced along with the Department of Highway and Railway Engineering of the Budapest University of Technology and Economics 9 specimens from every mixture, which makes a total of 81 samples. After performing the tests the master-curves at 20°C were determined as a function of the loading time. The fitting parameters are shown in Tables 3 and 4.

In the case of asphalt mixtures a variety of recommended values for the constant C used in the Arrhenius equation can be found in international papers, e. g:

- C = 10920 K, (Francken et al, 1988)
- C = 13030 K , (Lytton et al, 1993)
- C = 7680 K, (Jacobs, 1995)

Tab. 3. Fitting parameters for AC mixtures I.

Mixture Code	C	E∞	E0
mKL1	8 646	40 169	301
mKL2	9 357	29 714	344
mKL3	9 818	40 924	202
mKM1	10 317	50 530	148
mKM2	10 955	41 869	450
mKM3	9 624	38 988	486
mKH1	10 713	36 875	1 170
mKH2	11 937	54 650	20
mKH3	8 971	36 149	577

By using the value C as a dependent variable during the optimalization, we gained an additional parameter for the characterization of the mixture. Based on these values the activation energies can be determined. Although these are presumably characteristic for the mixture and the binder respectively, the validation of this assumption was not possible, since there was no further information on the binder available.

Table 3 also contains the estimated theoretical upper and lower stiffness limits for the mixture. Unfortunately the test results in some cases showed technically non-interpretable values, this can be explained with metrological anomalies, and inaccuracies, which occurred predominantly during the test, mainly at low temperatures. The present results arise from the processing of the entire test database that considering the results at different loads and temperatures represents more than thousand tests in total.

After the optimalization the parameters of the sigmoid function are also available, as shown in Fig. 4.

Tab. 4. Fitting parameters for AC mixtures II.

Mixture Code	γ	β	α	δ
mKL1	0,63805559	-0,04589	2,125888	2,478004
mKL2	0,74787816	-0,04663	1,936239	2,536729
mKL3	0,56066872	-0,13096	2,307115	2,304861
mKM1	0,66215506	0,011379	1,498572	3,068162
mKM2	0,39344786	-0,94469	3,436771	1,30082
mKM3	0,79970849	0,219456	1,796613	2,761479
mKH1	0,50471065	-0,4765	2,532929	2,170619
mKH2	0,57875821	-0,22081	1,968661	2,653236
mKH3	0,72531907	0,116833	1,904339	2,686597

So these parameters put us in a position, where the master-curves could also be determined as a function of the reduced frequency, as shown below.

In the Figs. 5, 6, 7 mixtures with the same aggregate, but different binder content are shown, these could be used for the investigation of the influence of the binder content variations. It can be seen, that on the diagrams showing the influence of the binder the stiffness curve of the mixture with binder content "3" is always the lowest, whereas the binder contents „2" and „1" have an approximately similar influence. The highest stiffness values were reached with the binder content „1".

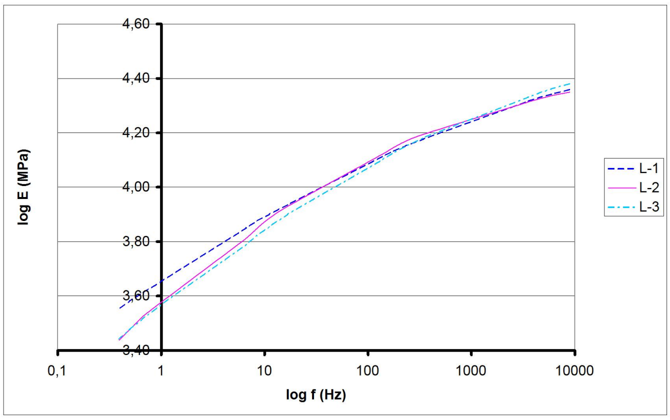

Fig. 5. Master-curves of the mixture "mKL-1… mKL-3"

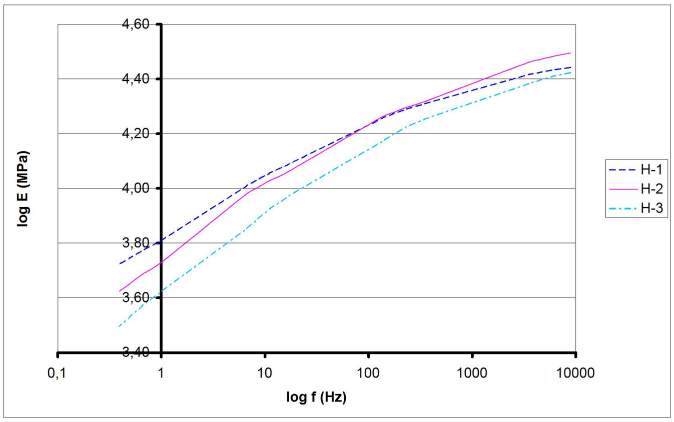

Fig. 6. Master-curves of the mixture "mKH-1…mKH-3"

In Figs. 8, 9, and 10 the master-curves are shown for mixtures with identical binder content, but different aggregates. The influence of the grain size distribution on the stiffness is clear. The lowest stiffness values always occurred at grain size distributions, which were designed significantly to the lower boundary, while the grain size distribution designed to the upper boundary and the distribution averaged between the boundaries resulted in approximately similar stiffnesses. It is surprising, that while during the lower and middle grain size distribution a significant difference can be observed, the middle and the upper grain size distributions do not show considerable affects.

4.1 Conclusions

As mentioned several times before, although the mixtures can be characterized with a single stiffness value at the compulsory temperature, the differences between the mixtures can not be determined to the full extent. It is long known that the temper-

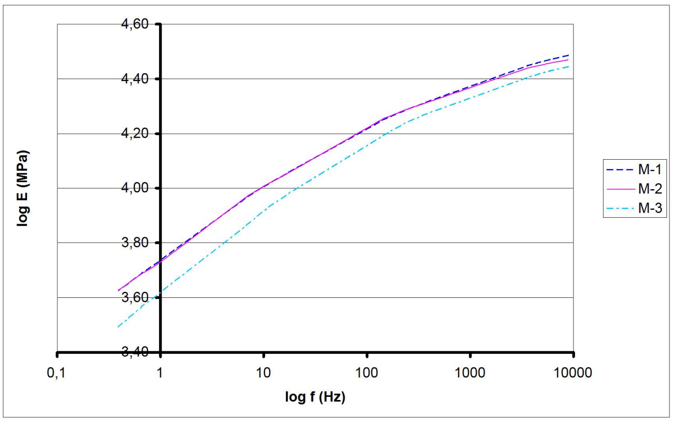

Fig. 7. Master-curves of the mixture "mKM-1…mKM-3"

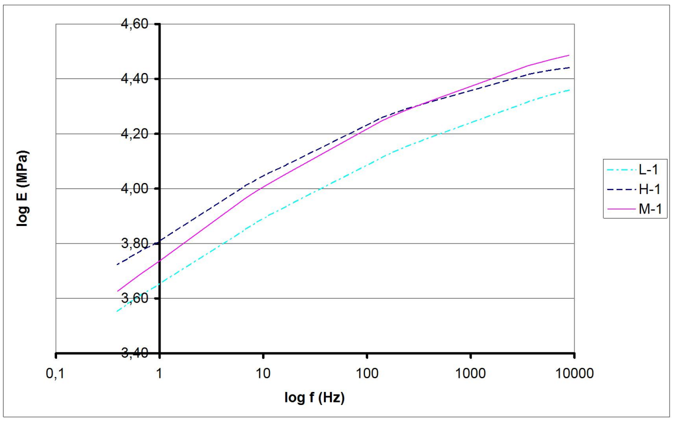

Fig. 8. Master-curves of the mixture "mK…1"

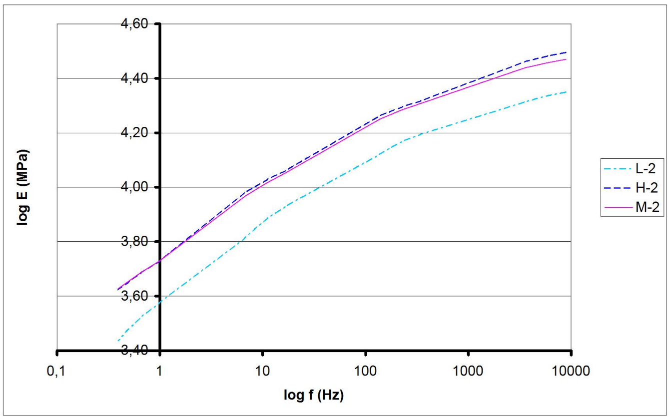

Fig. 9. Master-curves of the mixture "mK…2"

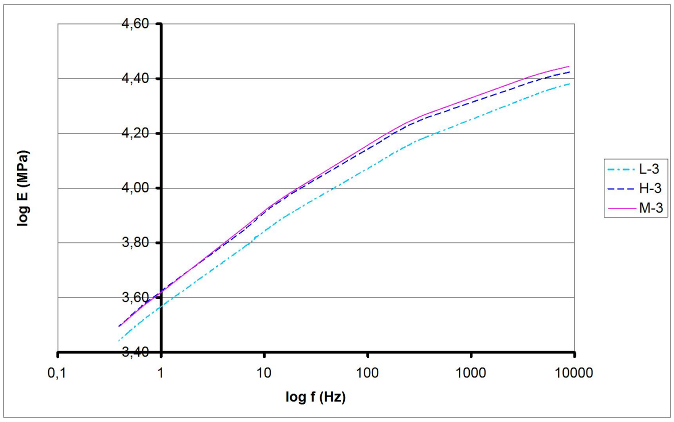

Fig. 10. Master-curves of the mixture "m. . . K3"

ature and the frequency dependence of the complex module can be regarded as the fingerprint of the material behavior, and thus is a relation of fundamental importance. A respectable Dutch workgroup emphasized in its recommendations for design system for asphalt track structures, that due to its valuable information content it is recommended to prescribe the determination of the master-curve in every case. The master-curves do not only supply information on the stiffness in dependence on the loading time and temperature, but also on the fatigue behavior of the asphalt mixture.

We would like to highlight, that in Hungary up till now test like these were not performed on asphalt mixtures, the cooperation of the H-TPA Ltd. and the BME is the first of these tests. According to our hopes during the test we proved, that the master-curve can be reconstructed with relatively simple resources, thus establishing the basics for later and more substantial engagement in this issue in Hungary (Fi–Pethő [1]).

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