The difference between the "ASTM approach" and the new "AASTHO approach" for Dynamic (Complex) Modulus

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Antonio Montepara
Professor
University of Parma - Department of Civil and Environmental Engineering and Architecture
Parco Area Scienze 181/A, 43100 Parma, Italy
Ph.:+39 0521 905904, Fax.: +39 0521 905924
e-mail: antonio.montepara@unipr.it

Arianna Costa
Associate Researcher
University of Parma - Department of Civil and Environmental Engineering and Architecture
Parco Area Scienze 181/A, 43100 Parma, Italy
Ph.:+39 0521 905907, Fax.: +39 0521 905924
e-mail: arianna.costa@unipr.it

Gabriele Tebaldi
Assistant Professor
University of Parma - Department of Civil and Environmental Engineering and Architecture
Parco Area Scienze 181/A, 43100 Parma, Italy
Ph.:+39 0521 905906, Fax.: +39 0521 905924
e-mail: gtebaldi@unipr.it

Synopsis

The reliability of asphalt pavement design is based on a correct characterization of the material performance. Particularly, the insight of stress strain curves and dynamic modulus of hot mix asphalt (HMA) is significant for an accurate road pavement design by means of rational computing methods.

This research investigates the differences between two different approaches for determining Dynamic (Complex) Modulus: the A.S.T.M. and the AASHTO methods.

The first uses the A.S.T.M. D 3497-79 testing: this test has been mostly used in the past and is still very common for dynamic modulus analyses.

Master curves of HMA dynamic modulus have been drawn by A.S.T.M. test data collection using the time-temperature superposition principle, which describes viscoelastic behavior of asphalt binders. Moreover the polynomial fitting function has been used for drawing a master curve that fashions a linear trend. Unfortunately, observing HMA physical performances, it shows a non-linear behavior between low and high temperatures. A big difference has been measured between values of complex modulus recordered during the test at a fixed temperature and the complex modulus calculated with master curve at the same temperature.

The second approach for Dynamic (Complex) Modulus followed the proposal of AASTHO specification; according to this method the master curve for asphalt mixtures was developed at the University of Meryland. The curves were drawn fitting a sigmoidal function to the measured compressive dynamic modulus tests data using non-linear least squares regression.

Moreover the research analyzed both the A.S.T.M. D 3497-79 and the AASTHO tests; according to the first test, at each temperature, the machine applies to the specimens the same load. At different temperatures the same load causes in the asphalt material a different stress level. On the contrast, in the AASTHO test, at each temperature, the machine applies to the specimens a different load but the same stress level.

In the research it has been possible to validate the AASTHO approach analysing two different materials. This approach shows the real physical behavior of HMA, while the comparison between the ASTM and AASTHO approach allows to quantify the differences between the two methods.

The difference between the “ASTM approach” and the new “AASTHO approach” for Dynamic (Complex) Modulus

Hot Mix Asphalt (HMA) is defined as an elasto plastic material featured by a complex mechanical characterization due to its susceptibility to temperature as well to load frequency. For pavement design, the above mentioned peculiarity makes difficult the computation hypotheses needed for simulating the in service conditions [1].

In the S.H.R.P program (Strategic Highway Research Program) the HMA response to traffic load transmissions was described by the introduction of the Complex Modulus parameter. This parameter is settled applying to the HMA specimen an axial sinusoidal compression load at a specific temperature and at a specific load frequency, in order to represent the stress configuration which subject the pavement share touched by the tire.

This parameter allows the estimation of a bituminous mix behaviour subjected to external stresses as well as a comprehensive insight of its dependence on temperature, load frequency and load intensity.

The specification which describes the computation methodology of asphalt mixture complex modulus is the ASTM D 3497-79. This specification prescribes the application of a sinusoidal load wave (which compression varies from 0 to 241 kPa) on cylindrical specimens, measuring the deformations occurring between the 30th and the 45th second in the test: after that this time is expired, the test can be considered over. Test temperatures imposed by the specification are 5°C, 25°C, 40°C and the load frequencies are 1Hz, 4Hz, 16Hz. Finally, this specification prescribes that the load wave applied on the specimen must be always the same regardless of the temperature and the load frequency of the test execution.

In the recent past, this approach has been discussed by many researchers whose investigated the performance characteristics of asphalt mixtures. According to this trend, in 2002 the AASTHO proposed a new test methodology to determinate HMA complex modulus, taking in account of the material susceptibility to both temperature and load frequency. Hence, in complex modulus tests, the idea of applying growing loads at decreasing temperatures was introduced to induce in the material the same effect at different temperatures. This idea was already been pointed out in the trial protocol for determining the resilient modulus in which load decreases when temperature increases to limit plastic deformations in asphalt mixture due to its elasto-plasto-viscous nature. The procedure proposed by the AASTHO consists in the test execution at -10°C, 4.4°C, 21.1°C, 37.8°C, 54.4°C temperatures and at 0.1Hz, 0.5Hz, 5Hz, 10Hz, 25Hz load frequencies for each temperature, starting from the lowest. The test individualizes the application of a sinusoidal load in a cyclic way. This load should be steady to obtain a deformation between 50 and 150 μmm/mm. Mostly, the dynamic load value varies between 15 and 2800 kPa: the lowers are both temperature and load cycle number, the bigger are dynamic load values which depend also on the frequency. These two approaches lead to results which are numerically similar but representing two conceptually distinct conditions.

This paper presents the results of a comparison between the two approaches, aimed at the evaluation of the common points and the employment limits, allowing an adequate use of the E* parameter in pavement computation software.

In specific, the two methodologies are been investigated analysing two distinct asphalt mixtures, verifying how much the new AASTHO approach, which bases on a termosensibility study of the material, leads to results comparable to those obtained by means of ASTM specification. Besides, the research investigates on the material behaviour at temperature and frequency ranges different from the ASTM specification, in particular at temperature lower to 5°C, higher than 40°C or at low load frequencies.

The complex modulus

In uniaxial stress condition, complex modulus is defined as the ratio between the sinusoidal tension of the beat ω applied to the material ($\sigma(t) = \sigma_0 \cdot sen\ \omega t$) and the sinusoidal deformation ($\varepsilon(t) = \varepsilon_0 \cdot sen\ (\omega t - \phi)$):

$$E^* = \frac{\sigma(t)}{\varepsilon(t)} \qquad 1.1$$

The absolute value of complex modulus |E*| is called dynamic modulus.
Using the imaginary notation, complex modulus can be written as[2]:

$$E^* = |E^*| \cdot \varepsilon^{i\phi} = E_1 + i \cdot E_2 \qquad 1.2$$

where:

- $|E^*| = \sigma_0/\varepsilon_0$ is the absolute value of the complex modulus (called stiffness modulus and indicated as S_m) representing the parameter needed for pavement design.
- ϕ is the argument of the complex modulus representing the phase displacement between stress and strain; it measures the viscous behaviour of the material, being zero in totally elastic materials and 90° in totally viscous materials.
- $E_1 = |E^*| \cdot \cos\phi$ is the real part of complex modulus representing the elastic component; it is called returning modulus.
- $E_2 = |E^*| \cdot sen\phi$ Is the imaginary part coefficient of complex modulus representing the viscous component; it is called dissipating modulus.

Complex Modulus is strictly connected with the phase angle, which represents the phase displacement between stress applied and strain measured.
The absolute value of complex modulus $|E^*|$ and the phase displacement ϕ variation depend on frequencies and temperatures; these parameters can be assumed representative of material termosensibility, becoming significant for studying asphalt mixture performances.

Master curves

To extend complex modulus values (obtained by a restricted number of tests) to any condition of load frequency and in service temperature, the so-called master curves are exploited using the time-temperature overlap principle[3].
According to this principle, test results obtained at specific temperature values, might be "translated" in connection with load or frequency time-rating to achieve a matching of the different curves, leading to one single master curve. The *"shift factor"* a_T defines the translation needed to shift from master curve data at the reference temperature to master curve data at any other temperature. To draw a master curve, a reduced frequency f_r is needed, achievable by dividing the frequency to the shift factor:

$$f_r = \frac{f}{\alpha_T} \qquad \text{or} \qquad \log(f_r) = \log(f) - \log(a_T) \qquad 1.3$$

The shift factor corresponding to the reference temperature must equal 1.
Many way to make the time-temperature overlap principle well-working can be found, usually the following two equations are proposed[4][5]:

- *WLF* (Williams, Landel, Ferry) equation:

$$\log(\alpha_T) = \frac{-C_1 \cdot (T - T_S)}{(T - T_S) + C_2} \qquad 1.4$$

with C_1 e C_2 constants

- Arrhenius equation:

$$\ln(\alpha_T) = 0,4343 \cdot \frac{\delta H}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_S} \right) \qquad 1.5$$

with:

- dH is an apparent activation energy which characterizes the material (in the order of 210 *kJ/mol*)
- R Is the ideal gas constant, equals to 8,314 $J/(K \cdot mol)$
- T, T_S Is the temperatures in Kelvin degrees.

Master curves, drawn by complex modulus experimental values obtained at 5°C, 25°C and 40 °C according to ASTM specification, show a linear behaviour representative of the physic behaviour of the material in that only specific range of temperatures; actually, shifting from low to high temperatures, asphalt mixture show a not direct proportion between complex modulus, temperature and load frequency.

In the last few years, the HMA behaviour based research discussed these issues; a new method for drawing master curves was developed by Pellinen [6], Witczak et alt. [7][8] whose at first introduced the sigmoidal function to model the asphalt mixture behaviour taking in account of both temperature and load frequency susceptibilities.

In this approach, master curves are drawn using the following sigmoidal equation[1]:

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta-\gamma\log(f_r)}} \qquad 1.6$$

where:

log|E*|	is the dynamic modulus logarithm
δ	is the lowest modulus value
f_r	is the reduced frequency
α	represents the amplitude of experimental complex modulus values.
β,γ	are parameters connected: the first to the horizontal position of the function change in concavity, the second to the slope.

The exploitation of a sigmoidal function for the interpolation of complex modulus experimental data, is explained by the physic behavior of the material.

The upper part of the sigmoidal function tends asymptotically to the higher stiffness of the material which depends on the higher stiffness of the mastic at low temperatures.

At high temperatures, the aggregate influence becomes very significant: the dynamic modulus value tends to adjust to a limit value depending on the material aggregate graduation.

The sigmoidal function renders the physic behavior of asphalt mixtures using a cyclic compressive load in all the temperature range.

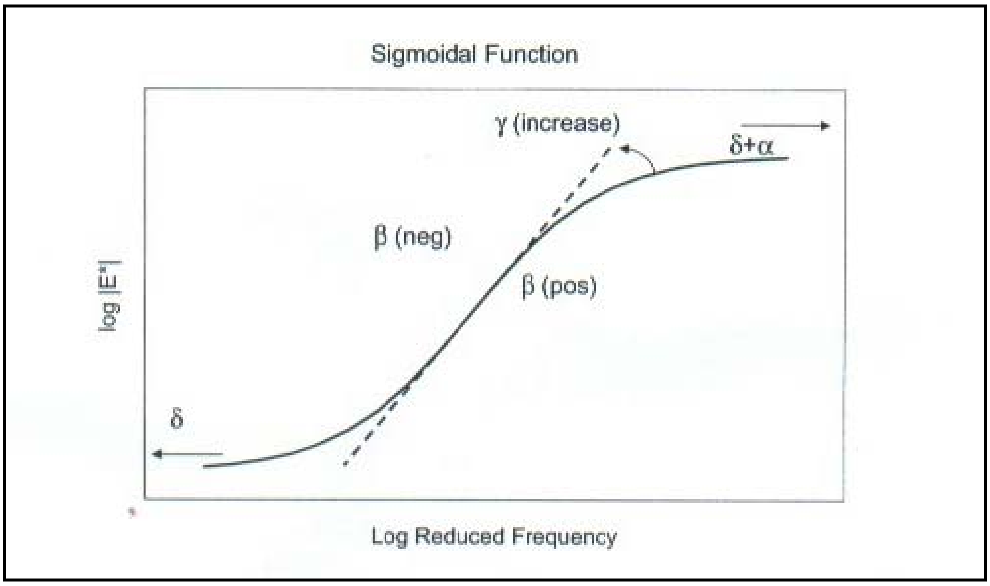

Figure 1 [1]: Sigmoidal Functions

Costa [9], Montepara et alt. [11] have studied HMA termosensibility finding that, employing the ASTM approach and extending the analyses at lower temperature respect the least indicated, the master curve keeps a linear trend without mentioning the asymptotic behaviour showed by the real material analysis.

EXPERIMENTAL INVESTIGATION

The research was carried out performing and testing in laboratory two different asphalt mixtures bounded by natural mastic. The mixtures, called B57 and C56, were representative of the materials usually tested by this kind of test:

- B57 is a base layer 25-mm nominal maximum size mixture with a natural asphalt binder of 50/70 PEN bitumen;

- B57 is a binding layer 12.5-mm nominal maximum size mixture with a natural asphalt binder of 50/70 PEN bitumen;

A.S.T.M. D 3497-79 approach

These materials were tested using the A.S.T.M. D 3497-79 specification to determine complex modules extracting master curves.

These curves were extracted fitting the data obtained at specification temperatures (5°C, 25°C, 40°C) using Arrhenius equation and choosing T_S = 25°*C* (298 *K)* as reference temperature and the following α_T values:

Tab 1: α_T coefficients for each investigated temperature, T_s=25°C

T (*K*)	273	278	288	294.1	298	313
a_T	29.108	14.130	3.590	1.629	1	0.171

Complex modulus and phase angle master curves agree well with the behaviours, described in literature, of these parameters: IE*I increases at temperature decrease and at frequency increase, according to the material stiffness increase at temperature decrease and at viscous component decrease due to load frequency increasing.

The same remarks can be done for φ which shows an opposite behaviour, except at high temperatures. As already observed, even in this case [Fig.2] master curves, in a bilogarithm plane, behaves linearly.

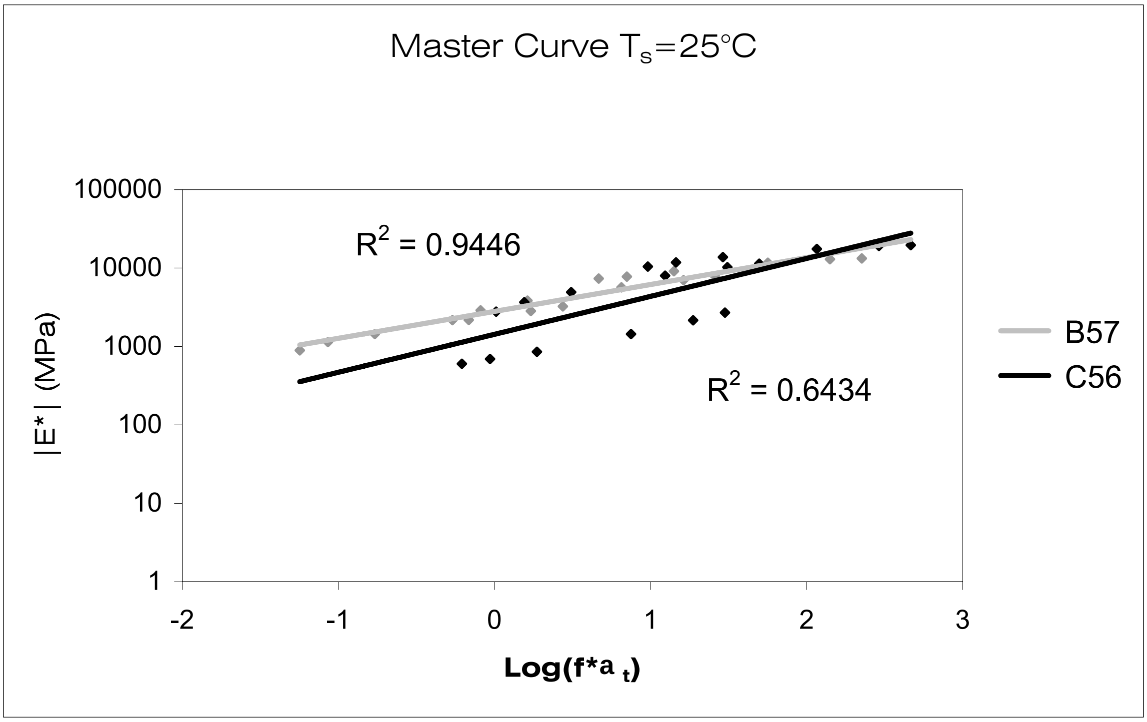

Figure 2: Master curves of B57 and C56 dynamic modulus

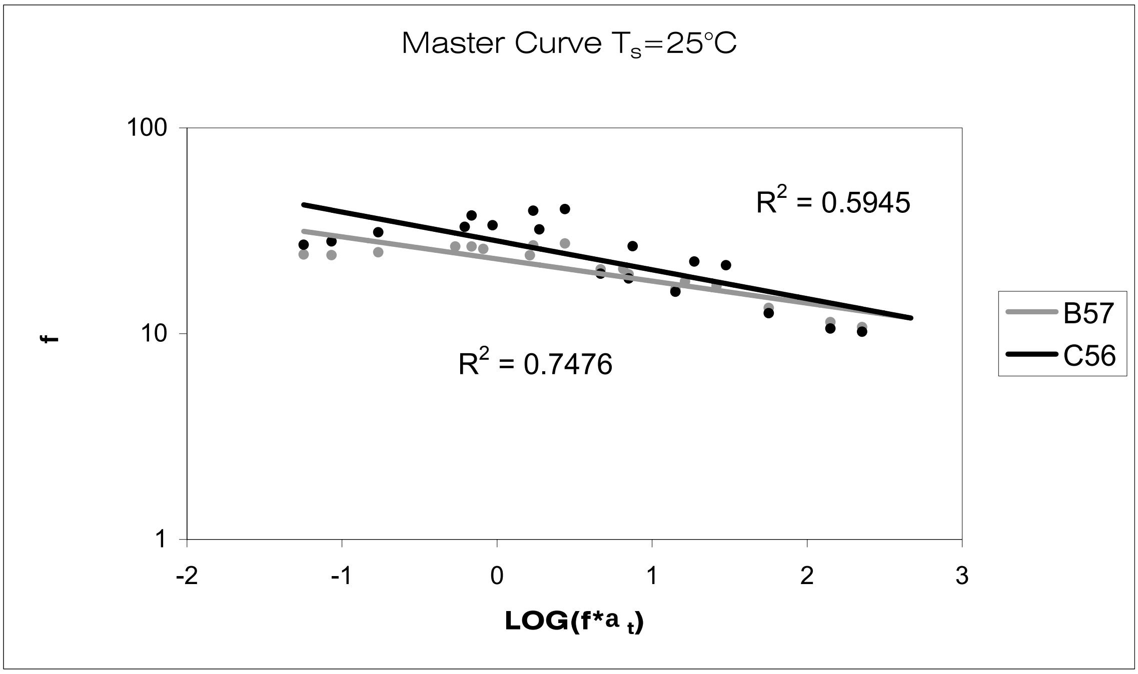

Figure 3: Mixes B57 e C56: phase angle master curves

Afterwards, a second replication of complex modulus tests was performed, extending both temperature and frequency ranges imposed by ASTM specification: 0°, 15°C temperatures and 0.33, 0.5 , 10 Hz load frequencies were involved in the investigation.
In this case, even if a shift in the material behaviour is evident, no important changes in master curve representations occur.

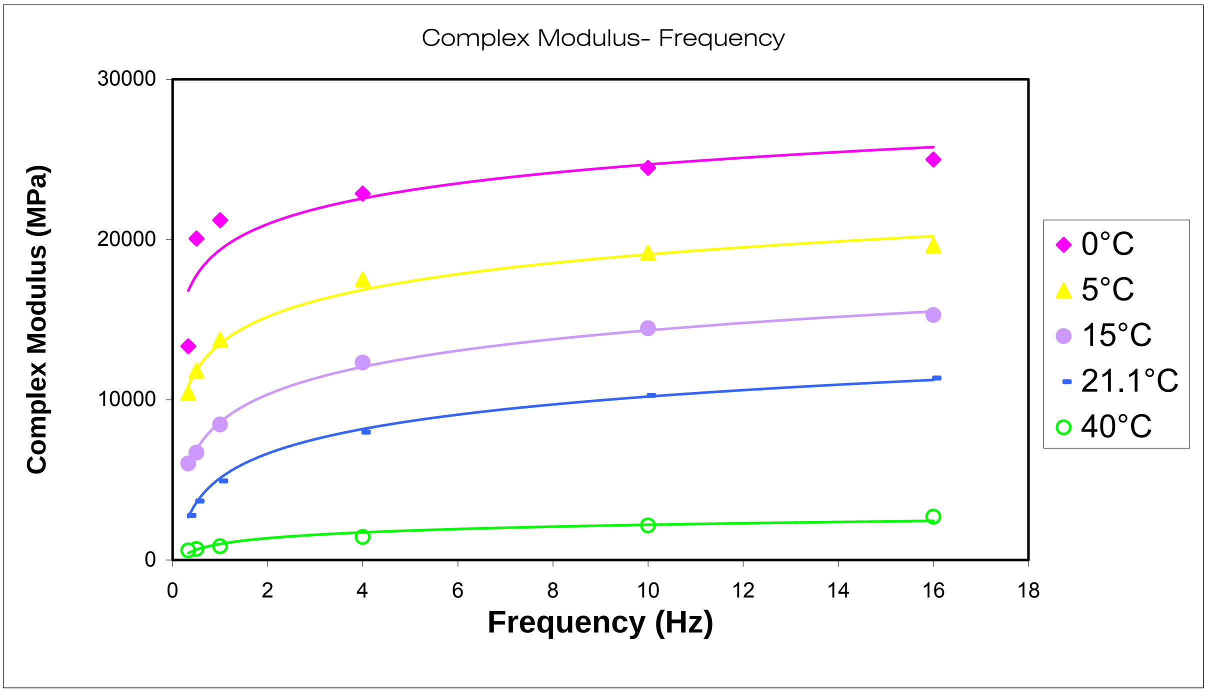

Figure 4: C56: effect of temperatures and frequencies on dynamic modulus

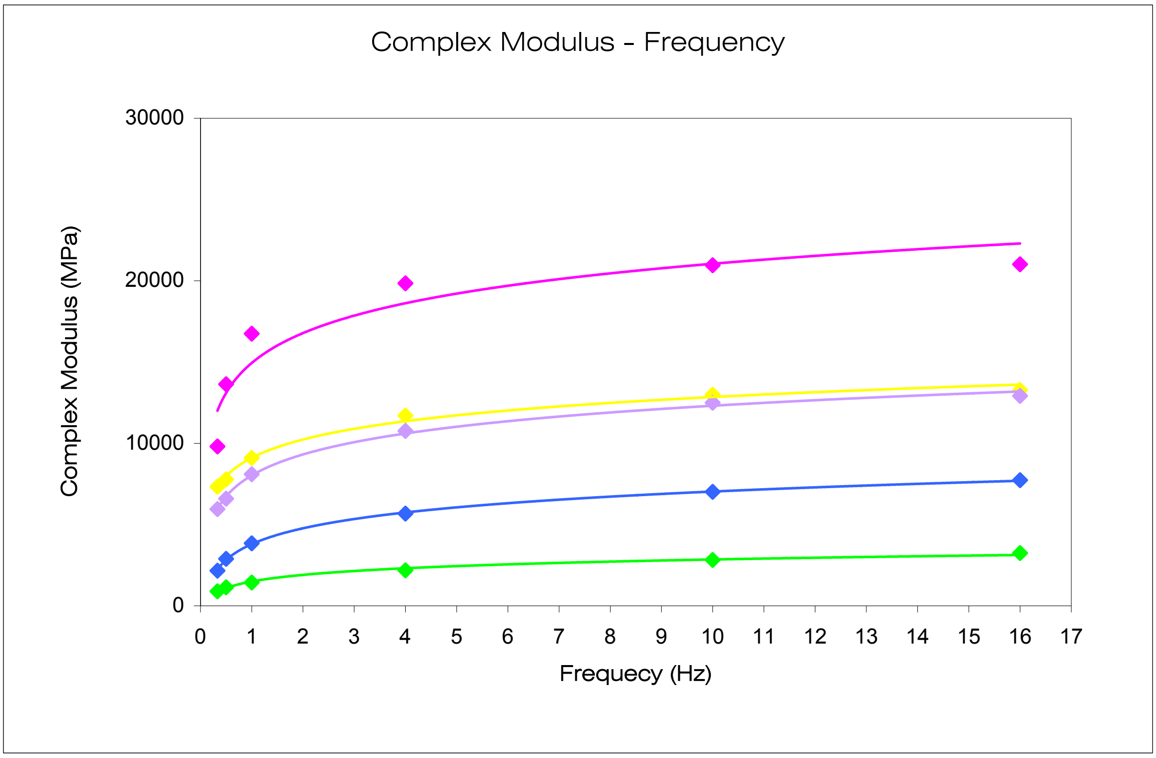

Figure 5: B57: effect of temperatures and frequencies on dynamic modulus

At this point, a verification of master curves effectiveness in result interpretations was required: complex modulus and phase angle values obtained at 0° and 15°C temperatures and 0.33, 0.5, 1, 4, 10, 16 Hz (Data$_{\text{Experimental}}$) were compared to those extrapolated at the same temperature and frequency conditions shifting the master curves obtained previously from ASTM specification data (Data$_{\text{theoretic.}}$)

Tab 2: Comparison between experimental and theoretical data

MIX C56								
f	Temperature 0°C				Temperature 15°C			
	$E^*_{theor.}$	$E^*_{exp.}$	$\varphi_{theor.}$	$\varphi_{exp.}$	$E^*_{theor.}$	$E^*_{exp.}$	$\varphi_{theor.}$	$\varphi_{exp.}$
16	45639.9	24991.178	11.91	7.39	16128.90	15286.18	16.31	18.99
10	36683	24474.414	12.72	8.44	12963.57	14467.83	17.42	16.82
4	23960.3	22866.713	14.47	11.20	8467.44	12325.36	19.82	21.05
1	12578.8	21212.646	17.58	11.66	4445.28	8463.41	24.08	24.69
0.5	9114.08	20057.3	19.38	13.32	3220.87	6699.77	26.54	26.11
0.33	7513.32	13349	20.55	13.57	2655.17	6021.17	28.13	31.24

MIX B57								
f	Temperature 0°C				Temperature 15°C			
	$E^*_{theor.}$	$E^*_{exp.}$	$\varphi_{theor.}$	$\varphi_{exp.}$	$E^*_{theor.}$	$E^*_{exp.}$	$\varphi_{theor.}$	$\varphi_{exp.}$
16	23055.1	21017.543	11.92	8.37	11243.17	12918.38	14.93	13.86
10	19621.3	20955.385	12.54	9.33	9568.59	12494.14	15.70	13.86
4	14327.8	19850.128	13.84	10.28	6987.16	10768.80	17.33	16.10
1	8904.11	16747.081	16.06	11.54	4342.22	8098.29	20.11	19.73
0.5	7019.34	13636.348	17.30	11.91	3423.08	6591.34	21.66	22.23
0.33	6086.61	9808.8563	18.09	13.32	2968.22	5948.44	22.65	25.76

The results show differences between theoretical and experimental data; these differences become considerable at test frequency decreasing. The comparison between IE*I values obtained shifting master curves and those experimentally determined points out for each mixture a discrepancy which might be acceptable at high frequencies, becoming enormous at low frequencies. The same remark can be done for φ values, taking in account that in this case the deviation is not so relevant that in complex modulus.

AASHTO approach

The two mixtures where then tested by means of AASHTO specification.

The substantial differences compared with the ASTM approach consist in wider frequency and temperature ranges, as well as in the explicit counting of the termdependence of material performances: the load entity is, for this reason, fixed on the induce deformation dependence. To do that, the load is settled at each temperature to obtain constant deformations, in detail, stress values are suggested [Tab. 3] and then calibrated according to the real registered deformations.

Tab 3: Typical Dynamic Stress Levels

Temperatura (°C)	**Range (kPa)**
-10	2800
4.4	1400
21.1	700
37.8	250
54.4	70

Also the number of load cycles depends on the frequency as shown in the following table:

Tab 4: Number of Cycles for the Test Sequence

Frequecy (Hz)	**Number of Cycles**
25	200
10	200
5	100
1	20
0.5	15
0.1	15

As observed in the values obtained by A.S.T.M protocol, even in this case the analyzed mixes show $|E^*|$ growing at temperature decrease and at frequency increase and a phase angle which grows at temperature increase and at frequency decrease, showing a changeable behaviour at high temperatures (37.8°C, 54.4°C).

In this case, master curves were drawn using the methodology indicated by Pellin, considering 21.1°C as the reference temperature and interpolating the points on the graph to obtain a 2-apsynthotic behaviour: the lower one equals zero, while the higher one corresponds to the biggest material stiffness, coherently with the physic behaviour of asphalt mixtures.

Tab 5: a_T coefficient for each analysed value of temperature, T_s=21.1°C

T (K)	263	277.4	294.1	310.8	327.4
a_T	82.328	9.445	1.000	0.135	0.023

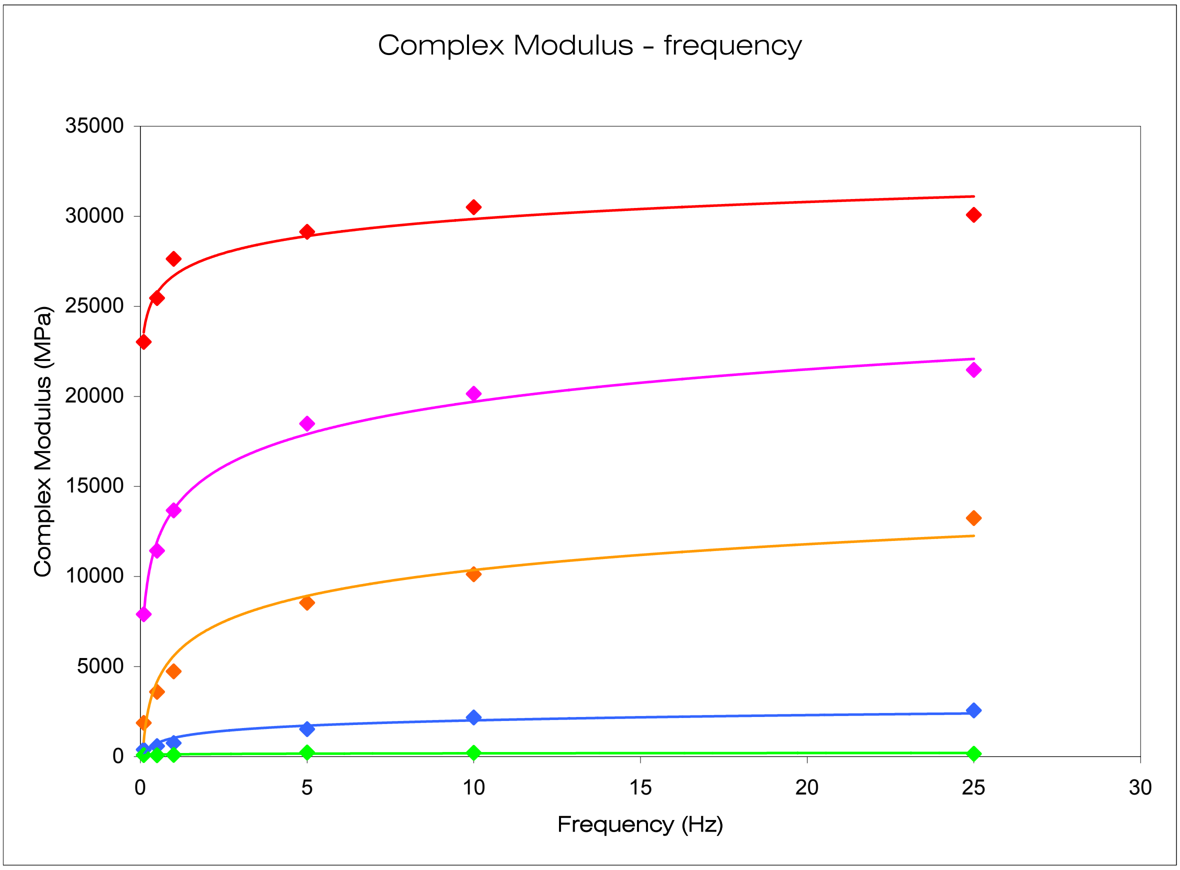

Figure 6: Effect of temperatures and frequencies on the C56 mix dynamic modulus

Compared with the previous test results, the difference between IE*I values is clearly more evident at different temperatures; besides, employing shift factors computed by means of the W.L.F. (Tab. 5) equation, and drawing master curves, the difference regarding ASTM data results macroscopic. Particularly in this case it's evident the representation of two asymptotic trends, characteristics of the real material behaviour.

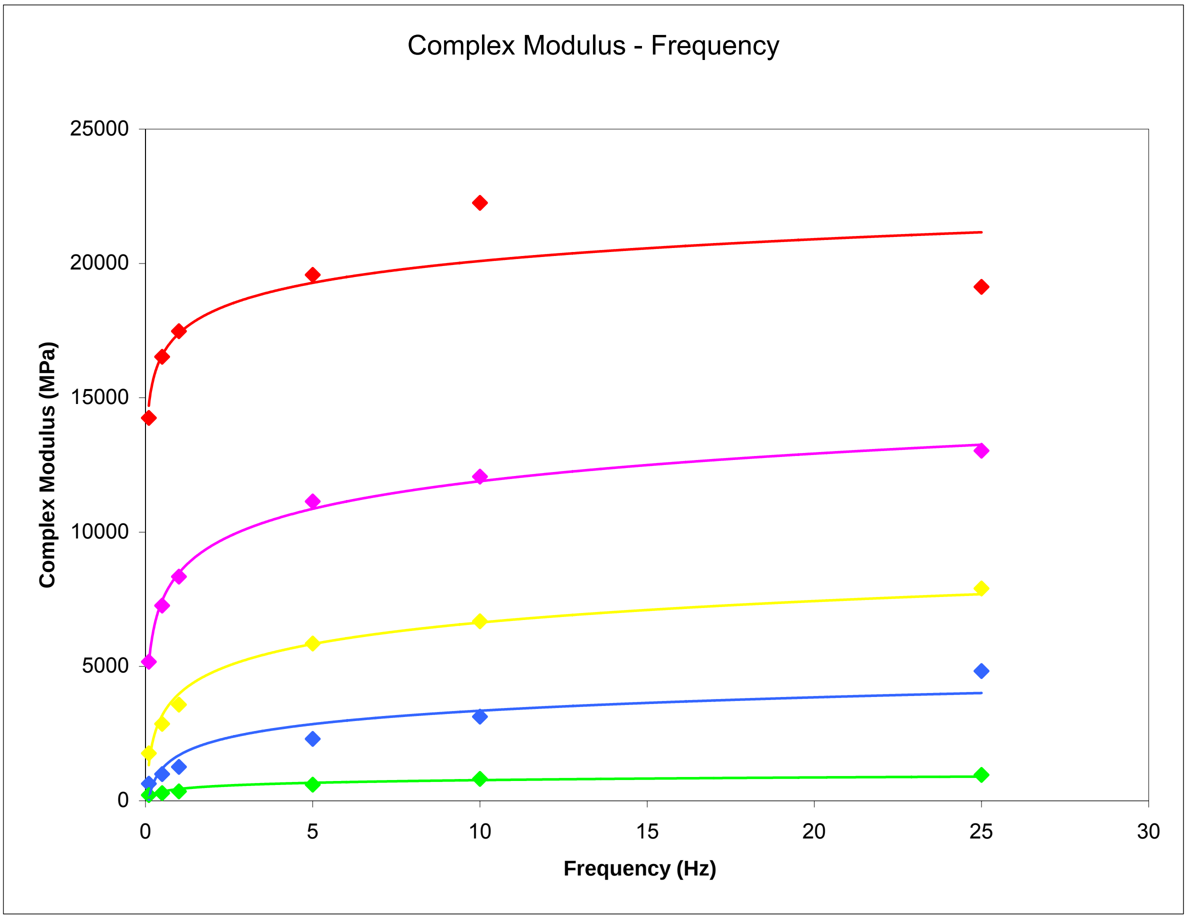

Figure 7 – Effect of temperatures and frequencies on B57 mix dynamic modulus

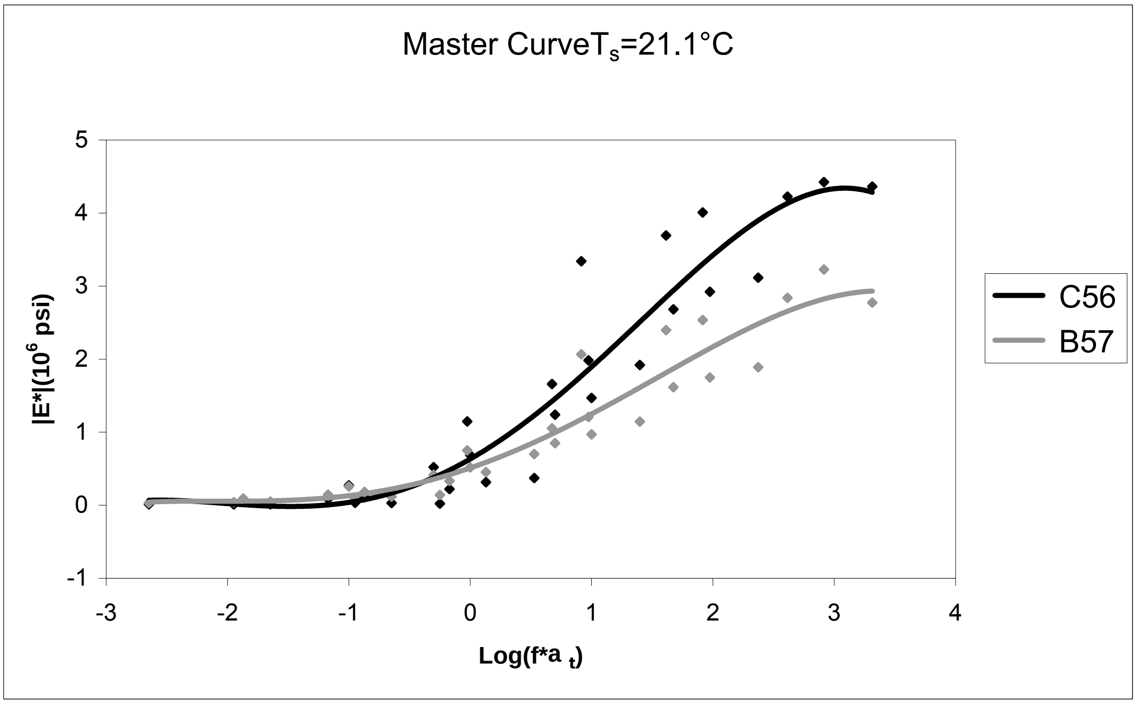

Figure 8 – Master curve of B57 and C56 dynamic modules, T_s=21.1°C

Conclusions

In the present experimental research complex modulus master curves were drawn following two different approaches: the first one according to A.S.T.M. D 3497-79 specification, the second one following the new AASHTO proposal which, taking in account of the non linear behavior of asphalt mixtures, suggests to vary the load entity depending on the temperature and the frequency of loading.

By means of the master curve obtained by ASTM employment, it was possible to determine the complex modulus values at 0°c and 15°C, comparing those with the experimental values obtained by laboratory analysis.

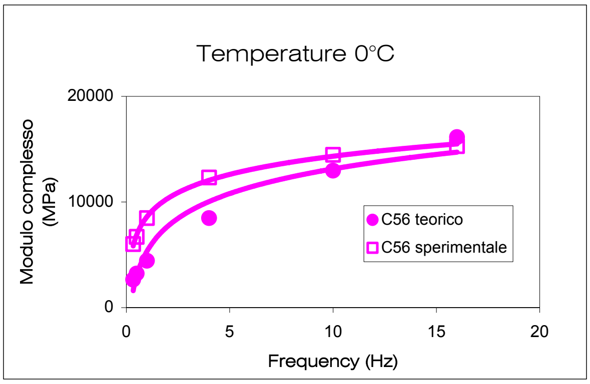

Figure 9 - C56 comparison between theoretical and experimental data at 0°C

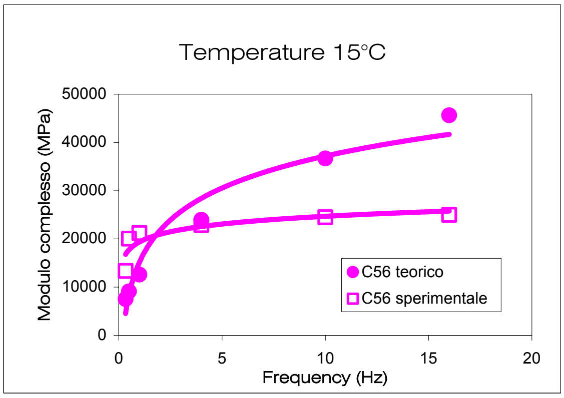

Figure 10 - C56 comparison between theoretical and experimental data at 15°C

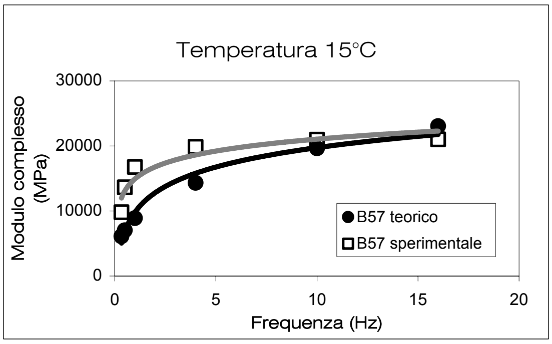

Figure 11 - B57 comparison between theoretical and experimental data at 15°C

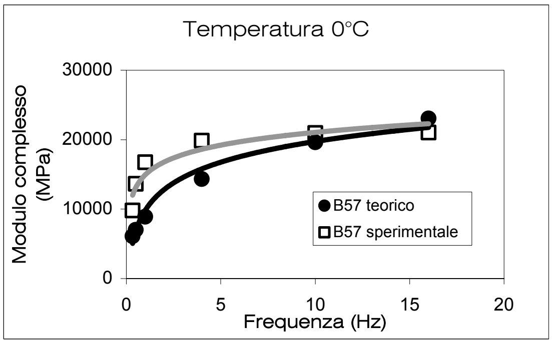

Figure 12 - B57 comparison between theoretical and experimental data at 0°C

From the comparison it was noted that mater curves obtained from A.S.T.M. approach allows an acceptable material physic interpretation at temperatures within the range proposed by the specification. Actually, if the comparison is carried out at frequencies lower than 1Hz, the difference between the modulus value extrapolated from master curves and that one obtained from experimental data, increases considerably; sometimes it could show some inaccuracies even for values within the proposed range. This realization confirmed the need of individuating a specific test which allows the analysis of the real material behaviour, even at temperatures and/or frequencies different from those imposed during laboratory tests (at the AASHTO proposal basis).

From the AASTHO approach investigation it was noted that the upper part which coincides with high load frequencies and low test temperature, tends asymptotically to the highest value of the material stiffness, which strictly depends on the stiffness of the mastic employed.

At high temperatures, the influence of aggregates becomes significant: the dynamic modulus value tends to fix around a limit value depending on the lytic skeleton of the mixture.

It can be concluded that the traditional approach for complex modulus determination following the ASTM 3497-79 specification, should be still employed when an evaluation of the material performance within 5°÷40°C temperature range is reached. If the aim is to characterize the material at as much as possible general conditions, particularly as the support of a pavement design, it is absolutely required to proceed by ASSTHO specifications, obtaining the curves according to sigmoidal curve approach.

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