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Performance Oriented Requirements for Bituminous Mixtures

Performance orientierte Mischgutanforderungen

Spécifications des enrobés orientés performances

Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf
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Contents

Zusammenfassung

Die Europäischen Normen legen die Verfahren fest zur Charakterisierung der Steifigkeit und Ermüdung von Asphalt durch verschiedene Prüfungen, inklusive Biegeprüfungen. Die Prüfungen werden an verdichtetem Asphalt unter sinusförmiger Belastung unter Verwendung verschiedener Probekörpertypen und Auflagerungen vorgenommen. Die Verfahren dienen zur Einstufung von Asphalt aufgrund seiner Steifigkeit und als Hinweis auf sein relatives Leistungsvermögen in der Fahrbahnbefestigung. Sie dienen somit dazu, Daten zur Abschätzung des Tragverhaltens in der Strasse zu erhalten und Prüfdaten bezüglich der für Asphalt geltenden Anforderungen zu beurteilen. In diesem Projekt wurden Zweipunkt-Biegungen an trapezförmigen Prüfkörpern (2PB-TR) und Vierpunkt-Biegungen an prismatischen Prüfkörpern (4PB-PR) durchgeführt.
Mit Hilfe leistungsorientierter Anforderungen kann die erwartete Lebensdauer von Asphalt Belägen verlängert werden. Gegenwärtig erhält die Schweizer Norm Anforderungen für AC-EME [SN 640 431-1b-NA].

Ziel dieses Projektes war es, 2PB und 4PB Biegeprüfungen nach Europäischer Norm an Asphalt Prüfkörpern durchzuführen, um abzuklären, ob beide Prüfungen die gleichen Ergebnisse hinsichtlich Rangierung liefern und ob eine Beziehung zwischen beiden Verfahren existiert. Die Prüfungen wurden an Riegeln durchgeführt, die aus verschiedenen befahrenen Autobahnstrecken entnommen wurden. Diese Beläge waren 1 bis 14 Jahre alt. Durch Prüfung von Körpern aus Belagsriegeln wurde der Einfluss der Labor-Verdichtung eliminiert.

Insgesamt wurden 252 Prüfungen an acht Mischgutvarianten aus Schweizer Autobahnen durchgeführt. Die Steifigkeits-Prüfungen zur Ermittlung von komplexem Modul und Phasenwinkel wurden bei Temperaturen von 10°C, 15°C und 20°C jeweils bei Frequenzen von 3, 10 und 25 Hz durchgeführt. Die Ermüdungs-Prüfungen wurden bei 10°C und 25 Hz für 2PB-TR sowie 20°C und 25Hz für 4PB-PR durchgeführt, jeweils weggesteuert, wie in der Norm vorgeschrieben.

Die Ergebnisse zeigen, dass die Werte von komplexem Modul und Phasenwinkel bei 4PB-PR Körpern mehrheitlich höher sind als bei 2PB-TR. Dabei war die Differenz am geringsten für AC 22.
Aus allen Daten für komplexen Modul und Phasenwinkel, die bei Temperaturen von 10, 15 und 20°C sowie Frequenzen von 3, 10 and 25 Hz ermittelt wurden, ergab sich eine lineare Regression zwischen den Werten für 2PB-TR und 4PB-PR mit einem Korrelationskoeffizienten R^2=0.84 für den komplexen Modul und R^2=0.76 für den Phasenwinkel.
Der rein elastische Modul für 2PB-TR und 4PB-PR, also der Modul bei niedrigen Temperaturen bzw. einem Phasenwinkel von 0° im Black Diagramm, war jedoch meist unterschiedlich.

Die Ergebnisse zeigen auch, dass trotz höherer Streuung bei den 4PB Resultaten mit normkonform durchgeführten Prüfungen beim komplexen Modul praktisch gleiche Rangierung der Resultate erzielt wurde, dass aber beim Widerstand gegen Ermüdung für 4PB und 2PB die Rangierung nicht in allen untersuchten Fällen gleich war. Dabei ist zu berücksichtigen, dass die Prüfungen bei unterschiedlichen Temperaturen durchgeführt wurden.

Auf Basis der im Projekt durchgeführten Experimente wurden Werte für den Modul und den Widerstand gegen Ermüdung als Anhaltspunkte für die Normierungsarbeit ermittelt, wobei berücksichtigt werden muss, dass die Ergebnisse in diesem Projekt von Belägen stammen, die unterschiedlich gealtert und durch den Verkehr vorbelastet waren und nicht mit neuen im Labor hergestellten Materialien gleichzusetzen sind.

Die hier untersuchten Belagsprüfkörper erfüllen die Anforderungen gemäss nationalem Anhang für AC EME 22. Als Grundlage für die Normierung wird jedoch empfohlen, die Anforderungen an den komplexen Modul und den Widerstand gegen Ermüdung gezielt in einem neuen Projekt an labormässig hergestellten Prüfkörpern aus typischem Schweizer Mischgut zu ermitteln.

Résumé

Les normes européennes spécifient des méthodes de caractérisation de la rigidité et du comportement en fatigue des mélanges bitumineux, par des tests alternatifs y compris les essais de flexion. Les tests sont effectués sous chargement sinusoïdal, sur des matériaux bitumineux compactés. Les procédures sont utilisées pour classer les mélanges bitumineux sur la base de la rigidité, comme une indication des performances relatives au revêtement et permettent d'obtenir des données pour estimer le comportement structurel en fonction des spécifications. Ce projet a permis d'élaborer des lignes directrices pour différents mélanges bitumineux en utilisant les essais de flexion, en deux points sur des éprouvettes de forme trapézoïdale (2PB-TR) et en quatre points (4PB-PR) sur des éprouvettes de forme prismatique.

L'utilisation d'exigences orientées performances, axées sur la durée de vie prévue de la chaussée peut être améliorée. Actuellement en Suisse, des exigences orientées performances concernent uniquement les AC EME, [SN 640 431-1b-NA].

L'objectif de ce projet a été de réaliser des tests 2PB et 4PB sur des échantillons d'enrobés, conformément aux normes européennes, afin de déterminer si les deux tests pouvaient être utilisés alternativement et déterminer une corrélation entre les résultats obtenus. Les tests ont été effectués sur des échantillons provenant de différentes couches de revêtement prélevés sur plusieurs sections de chaussées. Les structures prélevées et testées sont âgées de 1 à 14 ans. L'utilisation de structures prélevées in situ devaient permettre d'atténuer, dans une certaine mesure, l'effet de diverses méthodes de compactage en laboratoire.

Un total de 252 expériences ont été effectuées sur huit types de mélanges provenant du réseau autoroutier suisse. Les essais de rigidité pour déterminer le module complexe ont été réalisés à 10°C, 15°C et 20°C, à une fréquence de 3, 10 et 25 Hz. Les essais de fatigue ont été réalisés à 10°C / 25 Hz pour le test 2PB-TR et 20°C / 25 Hz pour le test 4PB-PR. Les deux essais contrôlés en déformation, tel que prescrit par les normes.

Les résultats présentés indiquent que le module complexe et les valeurs d'angle de phase des tests 4PB-PR sont systématiquement plus élevés que ceux des tests 2PB-TR tout en observant pour toutes les couches d'AC, une différence relativement faible.

La comparaison des résultats de rigidité et des angles de phases entre les tests 2PB-TR et 4PB-PR à 10, 15 et 25°C et 3, 10 et 25 Hz a montré dans le cas d'une régression linéaire, un coefficient de corrélation R^2 de 0.84 pour la rigidité et de 0.76 pour l'angle de phase.
Le module élastique pur obtenu à partir de diagrammes de Black, équivalant au module à basse température où l'angle de phase est nul, ne sont pas égaux dans la plupart des cas pour les tests 2PB-TR et 4PB-PR.

Les résultats obtenus dans ce projet, bien que ceux de l'essai 4PB montrent une dispersion plus élevée, indiquent une bonne similitude dans le cas de la rigidité (module complexe *E**) et une moins bonne correspondance entre les résistances à la fatigue, déterminées avec les essais de fatigue 2PB et 4PB.

Sur la base des expériences réalisées dans ce projet de recherche, des informations substantielles ont été obtenues pour le module complexe et la résistance à la fatigue.
Toutefois, il convient de noter que ces valeurs ont été obtenues en testant des matériaux mis en service depuis plusieurs années et non pas, par le test de matériaux neufs.

Les tests effectués dans ce projet répondent aux exigences de l'annexe nationale pour AC EME 22. Toutefois, dans l'objectif d'une normalisation, il est recommandé qu'un nouveau projet soit formulé pour définir, à partir d'échantillons produits en laboratoire, les valeurs de module complexe et de résistance à la fatigue relatives aux chaussées suisses actuelles.

Summary

The European standards specify methods for characterizing the stiffness and fatigue behavior of bituminous mixtures by alternative tests, including bending tests. The tests are performed on compacted bituminous materials under sinusoidal loading. The procedures are used to rank bituminous mixtures on the basis of stiffness, as a guide to relative performance in the pavement, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for bituminous mixtures. This project has developed recommendations for various asphalt concrete mixes used in Switzerland using the 2 point bending test on trapezoidal specimen (2PB-TR) and four point bending test on prismatic specimen (4PB-PR).
Using performance oriented requirements the expected life of pavements can be improved. Currently in Switzerland, performance oriented requirements exits for AC-EME, [SN 640 431-1b-NA].

The goal of this project was to perform 2PB and 4PB tests on asphalt samples in accordance to the European standards in order to determine if both tests could be used alternatively or if there is a relationship between the results. Tests were done on slabs from test sections that were sawn from trafficked road pavements. These slabs were from 1 to 14 years old when extracted. Field slabs were used in order to eliminate the effect of various laboratory compaction methods.

A total of 252 experiments were performed on eight types of mixes from Swiss motorways. Stiffness tests to determine complex modulus were performed at 10°C, 15°C and 20°C each at 3, 10 and 25 Hz frequency. Fatigue tests were performed at 10°C and 25 Hz for 2PB-TR tests and 20°C and 25Hz for 4PB-PR tests. Both in deformation control mode as prescribed by the standards.
The results presented indicate that complex modulus and phase angle values of 4PB-PR are consistently higher than 2PB-TR tests, although the difference for all AC 22 layers was minimal.

Using all complex modulus and phase angle data determined at 10, 15 and 20 °C and at 3, 10 and 25 Hz frequencies, a linear regression between 2PB-TR and 4PB-PR with correlation coefficient R^2=0.84 for complex modulus and R^2=0.76 for phase angle was obtained.
The pure elastic modulus, i.e. modulus at low temperature or zero phase angle, obtained from Black diagrams for the 2PB-TR and 4PB-PR tests are not equal in most cases.

In addition, the results in this project indicate that although there is more scatter in the 4PB results, for the tests that are performed according to the standards, for complex modulus the same ranking was obtained. However, keeping in mind that the tests were performed at different temperatures, fatigue resistance values obtained using 4PB and 2PB were not similar in each case studied.

Based on the experiments performed in this research project values were reported for complex modulus and resistance to fatigue as basis for further consideration for standardization. However it should be noted that these values were obtained using materials after being in service for several years and not for new materials.

The pavement specimens tested in this project fulfill the requirements in the national annex for AC EME 22. However, for the purpose of standardization it is recommended that a new project is formulated to define the required values for complex modulus and resistance to fatigue for lab specimens produced from current Swiss pavement mixtures.

1 Introduction

1.1 Scope

Stiffness and fatigue behavior of bituminous mixtures are characterized in the European standards by various methods including bending tests. The tests are performed on compacted bituminous materials under a sinusoidal loading or other controlled loading, using different types of specimens and supports. The procedure is used to rank bituminous mixtures on the basis of stiffness, as a guide to relative performance in the pavement, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for bituminous mixtures. This project has developed recommendations for ranking fatigue properties of various asphalt concrete mixes from real pavements in Switzerland with known performance, using the 2 point bending test on trapezoidal specimens (2PB-TR) and four point bending test on prismatic specimens (4PB-PR).

These recommendations are expected to serve as background for the expert commission EK 5.01 and EK 5.09 for the national annex to the European type testing standards. Because the tests presented in this report were conducted on samples from slabs taken from roads with known performance and not on fresh laboratory compacted samples, these recommendations can be used for establishing performance oriented requirements for standardization of the mixes. However, since the tests were not performed on fresh laboratory compacted samples, it should be noted that the moduli reported here may be higher and the fatigue life characteristics lower than those for freshly compacted samples used for type testing. This subject area would have to be investigated in another laboratory oriented study.

1.2 Project goals

The project aims to deliver the recommendations for establishing requirements for mixes based on fatigue test results and their field performance.

- How to implement performance oriented requirements
- Choice of tests
- Recommendations for the national annex for mix design

1.3 Background

Using performance oriented requirements the expected life of pavements can be improved. Various international and national research projects have shown that these requirements can improve the service life of pavements [Pittet 2000, 2006, Gubler 2009, Pais 2009]. Currently in Switzerland, performance oriented requirements exist for AC-EME, [SN 640 431-1b-NA]. Where, EME is the French abbreviation of enrobé module élevé which stands for high modulus asphalt concrete. The requirements specified are for complex modulus according to the European standards [EN 12607-26] and for fatigue behavior [EN 12697-24] as listed in Table 1. 1. The minimum required complex modulus S_{min} is defined at 15°C, 10 Hz. The current standard specifies fatigue resistance to be determined using the two point bending test on trapezoidal specimen only but no specific tests are mentioned for complex modulus. However, the national annex to the type testing standard [SN 640 431-20b-NA] mentions the 2PB-TR for both complex modulus (10°C 10HZ) and fatigue (10°C, 25Hz). The minimum strain ε_6, which is defined where 10^6 cycles, should be realized at 10°C, 25Hz is also specified in Table 1. 1. This specification is expected to ensure fatigue resistance.

Table 1. 1 Minimum requirements for high modulus AC EME [SN 640 431-1b-NA]

Class C	Complex Modulus S_{min} at 15°C, 10 Hz (2PB-TR) [MPa]	Fatigue resistance at 10°C, 25Hz [micro strains, µm/m]
AC EME C1	≥ 11000	≥ 100
AC EME C2	≥ 14000	≥ 130

The Swiss standard [SN 640 430b] defines the mix types (Table 1. 2) for asphalt concrete (AC) with the exception of AC EME, AC F, AC MR and AC RAIL. For the other mixes no type is defined.

Table 1. 2 Type of mixes

Type	Traffic
L	low
N	Moderate
S	heavy
H	Very heavy

Fatigue cracking is considered to be one of the primary failure modes in asphalt concrete. This type of failure can manifest itself in the form of reflective cracking as a result of repeated traffic loading [Di Benedetto 2004]. Determination of fatigue behavior of materials is standardized in many countries worldwide.

Although the 4PB test is considered not trivial by the scientific community, it has become a standard test method as it allows a significant section of the specimen to be exposed to fatigue loading. This aspect is discussed in more detail in chapter 5. Empa has traditionally used the coaxial shear test (CAST) to perform fatigue tests [Gubler 2005]. However, as this is a unique test not performed worldwide it has been difficult to compare results with other laboratories. Therefore EMPA has decided to investigate the 4PB test that incorporates the latest state of the art for 4PB testing and accounts for the concerns and developments worldwide with this type of test since the beginning of this project. This is especially true in the US where the 4PB is used as basis for the mechanistic empirical design guide (MEPDG) and the SHRP program [Pais 2009]. It is also reflected in different international conferences on 4PB fatigue testing, such as [Pais 2004][Paisy 2012] and intensive activities, e.g. by RILEM [Di Benedetto 2004]

Matthews et al (1993) investigated laboratory fatigue testing procedures for asphalt concrete mixtures. They summarized the steps necessary to measure fatigue lives in the laboratory and identified advantages and disadvantages of different methods. The three most promising methods are considered to be simple flexure, diametral fatigue, and tests based on fracture mechanics principles.

The result of a Rilem inter-laboratory study on various fatigue tests were presented by Di Benedetto et al (2004). Their results show that the classical fatigue approach is considerably influenced by test type and mode of loading (controlled stress or strain).They found that continuum damage models may serve towards a rational mechanistic fatigue characterization model.

Hartman and Gilchrist (2004) have incorporated a digitally imaged information system on fatigue cracking as a result of four point bending tests to measure the extent of damage and to characterize a linear elastic fracture mechanics model.

During a fatigue test three distinct regions can be identified. In region one, the reduction in stiffness decelerates, in region II the reduction is almost linear and in region III the reduction accelerates as shown in Figure 1. 1. The number of cycles $N_{f/50}$ where the initial E* modulus has been reduced by 50% can be taken as fatigue failure criterion. Also schematically shown in Figure 1.1 is the strain controlled fatigue failure curve. This Wöhler type of curve shows that continuously applying high strain amplitudes creates failure after fewer numbers of cycles than when applying low strain amplitudes. This allows defining another classical failure criterion ε_6 which denotes the applied strain (i.e. strain amplitude) where fatigue failure occurs just after 1 million cycles.

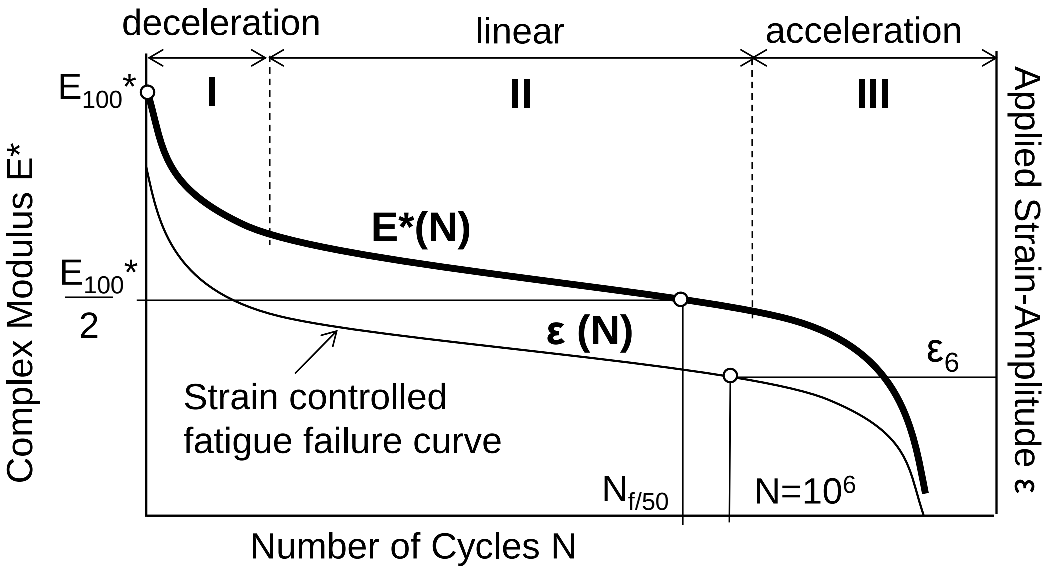


Figure 1. 1 Fatigue curves (complex modulus E(N) and strain controlled failure curve ε(N)) showing three distinct regions and different definitions for fatigue failure criteria*

The experience with 4PB tests in Portugal indicated that using laboratory produced samples at 20°C test temperature using any type of test set up can lead to a variability in complex modulus results of ±15 to 20%. The results for fatigue tests were reported as being similar [Picado-Santos 2009].

A Rilem inter-laboratory study [Francken 1998] has summarized the results of complex modulus measurements and fatigue behavior from fifteen laboratories. Various test setups were used including two 2PB-TR and three 4PB-PR setups. The results for complex modulus with measurements using small strains, and therefore in the linear elastic range of the material from the six laboratories that used 4PB-PR and 2PB-TR, are summarized in Table 1. 3. It is important to note that these tests were carried out on laboratory produced specimen. Tests were conducted at 0°C and 20°C and at 1 and 10 Hz each. Results shown in Table 1. 3 indicate that there is wider scatter in complex modulus at higher temperature and lower scatter in phase angle. As shown in this table**,** a maximum difference of 17 % in complex modulus at 20°C and 1 Hz and 24% in phase angle at 0°C and 10 Hz was measured. The general conclusion was that the bending tests were in close agreement compared to other tests performed in the study.

Table 1. 3 *Rilem interlaboratory results from 2PB-TR and 4PB-PR [Francken 1998]*

Lab code	**Test type**	**Spec Type**	**Complex Modulus E* [MPa] Temp [°C]/Freq [Hz]**				**Phase angle ϕ [°], Temp [°C]/Freq [Hz]**			
			0/1	**0/10**	**20/1**	**20/10**	**0/1**	**0/10**	**20/1**	**20/10**
B1	2PB	TR	12957	17920	2865	6056	10.9	8	31.2	24.6
CH2 (LAVOC)	2PB	TR	12260	16500	2995	5626				
F1	2PB	TR	14702	18251	3511	6563	9.7	7.6	27.7	21.2
NL2	4PB	PR	12219	16507	2130	4794	14.9	11.1	36	29.3
NL4	4PB	PR	13303	16952	2814	5683	10.4	8.3	31.1	24.7
NL5	4PB	PR	13500	17269	2874	5282				
	avg 2PB-TR		13306	17557	3124	6082	10	8	29	23
	avg 4PB-PR		13007	16909	2606	5253	13	10	34	27
	% diff		2	4	17	14	-23	-24	-14	-18

In September 2012 the third conference on four point bending was organized in Davis USA. The content of this last conference indicate that the use of four point bending as a tool for evaluation of fatigue resistance in asphalt concrete is increasing including its application in the mechanistic empirical design [Pais 2012].

1.4 Terminology [EN 12697-24:2012, EN 12697-26:2012]

This section defines some of the terminology used in this report in English, German and French. However, one has to keep in mind that the EN is not consistent in its terminology and its notations. For example, in [EN 12697-24] the complex stiffness modulus is denoted as S_{mix} whereas in [EN 12697-26] the complex modulus is called E*, or IE*I, in case of the absolute of the complex modulus. With respect to common scientific writing the latter notation and the wording “complex modulus” will be used in this report, wherever possible. Nevertheless, for completeness, the definitions as given in the European standards are summarized below.

1.4.1 English

complex modulus and phase angle

relationship between stress and strain for a linear visco-elastic material submitted to a sinusoidal load wave form at time, t, where applying a stress σ × sin (ω × t) results in a strain ε × sin (ω × (t − Φ)) that has a phase angle, Φ, with respect to the stress (EN 12697-26:2012)

fatigue

reduction of strength of a material under repeated loading when compared to the strength under a single load (EN 12697-24:2012)

conventional criteria of failure

number of load applications, $N_{f/50}$, when the complex stiffness modulus $S_{mix,0}$ (i.e. E^*_{100} in this report) has decreased to half its initial value (EN 12697-24:2012), see Figure 1.1

initial complex stiffness modulus

complex stiffness modulus, $S_{mix,0}$ (i.e. E^*_{100} in this report), after 100 load applications (EN 12697-24:2012), see Figure 1.1

Φ_{100} is in this report the corresponding initial phase angle

fatigue life of a specimen

number of cycles $N_{i,j,k}$ for specimen i corresponding to the chosen failure criterion j (e.g. conventional failure criterion j=f/50) at the set of test conditions k (temperature, frequency and loading mode) (EN 12697-24:2012),

strain ε_6, defined as strain at 10^6 cycles (EN 12697-24:2012), achieved under constant stress amplitudes, see Figure 1.1

1.4.2 German

komplexer Modul und Phasenwinkel

Zusammenhang zwischen der Spannung und der Dehnung für einen linear viskoelastischen Baustoff, der zur Zeit t einer Belastung mit sinusförmiger Wellenform unterzogen wird, bei der die Beanspruchung durch eine Spannung $\sigma \times \sin(\omega \times t)$ zu einer Dehnung $\varepsilon \times \sin(\omega \times t - \Phi)$ führt, die in Bezug auf die Spannung eine Phasenwinkel Φ aufweist (EN 12697-26:2012)

Ermüdung

Verringerung der Festigkeit eines Materials bei wiederholter Belastung im Vergleich mit der Festigkeit unter einer Einzellast (EN 12697-24:2012)

konventionelle Ausfallkriterien

Anzahl der Lastangriffe Nf/50, bei der sich der komplexe Steifigkeitsmodul $S_{mix,0}$ (i.e. E^*_{100} in diesem Bericht) auf die Hälfte seines Ausgangswertes verringert hat (EN 12697-24:2012), siehe Figure 1.1

anfänglicher komplexer Steifigkeitsmodul

komplexer Steifigkeitsmodul $S_{mix,0}$ (i.e. E^*_{100} in diesem Bericht), nach 100 Belastungen. (EN 12697-24:2012), siehe Figure 1.1

Φ_{100} ist in diesem Bericht der zugehörige anfängliche Phasenwinkel

Dauerhaltbarkeit eines Probekörpers

Anzahl der Zyklen Ni,j,k, für Prüfkörper i mit gewählten Ausfallkriterium j (e.g. konventionelle Ausfallkriterien j=f/50) bei einer gegebenen Reihe von Prüfbedingungen k (Temperatur, Frequenz und Belastungsart) entspricht (EN 12697-24:2012)

Dehnung ε_6, definiert als die Dehnung, die unter konstanter Spannungsamplitude bei 10^6 Zyklen erreicht wird (EN 12697-24:2012), siehe Figure 1.1

1.4.3 French

module complexe et angle de phase

relation entre la contrainte et la déformation pour un matériau à viscoélasticité linéaire soumis à une charge de forme sinusoïdale en fonction du temps, t, lorsque l'application d'une contrainte $\sigma \times \sin(\omega \times t)$ entraîne une déformation $\varepsilon \times \sin(\omega \times (t - \Phi))$ présentant un angle de phase, Φ, par rapport à la contrainte (EN 12697-26:2012)

fatigue

réduction de la résistance d'un matériau sous charge répétée, par rapport à sa résistance au premier chargement (EN 12697-24:2012)

critères conventionnels de rupture

nombre d'applications de charge, Nf/50, correspondant à une diminution de moitié du module complexe de rigidité, $S_{mix,0}$ (i.e. E^*_{100} dans ce rapport), par rapport à sa valeur initiale (EN 12697-24:2012), voir Figure 1.1

module de rigidité complexe initial

module de rigidité complexe, $S_{mix,0}$ (i.e. E^*_{100} dans ce rapport), après application de 100 chargements (EN 12697-24:2012), voir Figure 1.1

Φ_{100} est dans ce rapport angle de phase initial

résistance à la fatigue d'une éprouvette

le nombre de cycles, Ni,j,k, pour l'exemplaire i correspondant aux critères j (e.g. critères conventionnels de rupture j=f/50) de rupture conventionnels dans les conditions d'essai k(température, fréquence et mode de chargement) (EN 12697-24:2012),

déformation relative ε_6, correspondant à la déformation à 10^6 cycles (EN 12697-24:2012) obtenue avec amplitudes de contrainte constantes, voir Figure 1.1

2 European Standards

The European standards for stiffness [EN 12697-26] and fatigue tests [EN 12697-24:2004+A1] prescribe various methods. Here, the 2-point bending tests using trapezoidal specimen (2PB-TR) and four point bending using prismatic specimen (4PB-PR) are of interest. The following items are common for both tests:

1. The method can be used for bituminous mixtures with maximum aggregate size of up to 20 mm. This restriction is due to the various sieve sizes in the EU. In Switzerland the sieve size 22 mm is used as upper limit and therefore the specimens used in this project have a maximum aggregate size of 22 mm.
2. Specimens prepared in a laboratory or obtained from road layers with a thickness of at least 40 mm for 2PB-TR and 3*D for 4PB-PR.

The calculation of the complex modulus is described in detail in the standards and is repeated here for convenience. The complex modulus is characterized by of two components: The real part E_1 and the imaginary part E_2 as shown in equation (1) and (2) below and Figure 2. 1. The absolute value of the complex modulus E* (in [EN 12697-24] also called complex stiffness modulus) is calculated using equation 3 and the phase angle with equation (4).

$$E_1 = |E^*| \times \cos(\phi) \qquad (1)$$

$$E_2 = |E^*| \times \sin(\phi) \qquad (2)$$

$$|E^*| = \sqrt{E_1^2 + E_2^2} \qquad (3)$$

$$\phi = \arctan \frac{E_2}{E_1} \qquad (4)$$

In order to obtain E_1 and E_2 from the measurements of Force, F in Newton and resulting displacement z in mm and the phase angle ϕ in (°) the following expressions are recommended in the standard:

$$E_1 = \gamma \times \left(\frac{F}{z}\right) \times \cos(\phi) + 10^{-6} \times \mu \times \omega^2 \qquad (5)$$

$$E_2 = \gamma \times \left(\frac{F}{z}\right) \times \sin(\phi) \qquad (6)$$

Where ω is the angular frequency=2πf and f is the frequency in Hz. γ and μ are the form factor [1/mm] and mass factor [g] as defined in Table 2. 2.

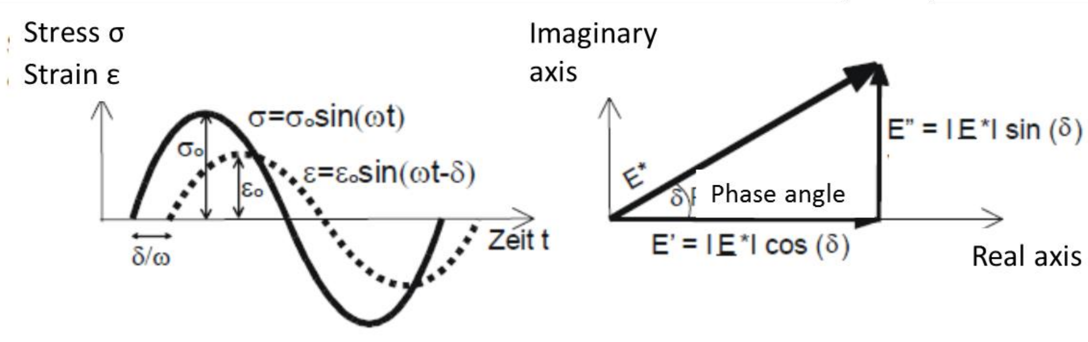


Figure 2. 1 Definition of complex modulus and phase angle

2.1 Test methods for hot mix asphalt – Part 24: Resistance to fatigue [EN 12697-24:2012+A1]

The concept of fatigue life is based on the idea that most materials undergo a gradual deterioration under repeated stresses that are much smaller than the ultimate strength of the material. Therefore, knowledge of fatigue behavior of asphalt concrete materials is imperative for material evaluation.

The 2PB and 4PB test methods may be used to characterize the behavior of bituminous mixtures under fatigue loading. The specimen is moved sinusoidally at the imposed displacement amplitude until it reaches a certain failure criterion. The goal is to measure the number of cycles N_i at failure in a Wöhler type of way. At least 18 specimens are tested. The strain ε_i is selected so that either the values are approximately regularly spaced on a logarithmic scale; or there are at least 3 levels of deformation, with a sufficient number of specimens at each level.

On the basis of the results representing the length of life N_i for a chosen strain ε_i, the fatigue line is drawn by making a linear regression between the decimal logarithms of N_i and the decimal logarithms of ε_i having the following shape:

$$\log(N) = a + \left(\frac{1}{b}\right) \bullet Log(\varepsilon) \quad (7)$$

$$\varepsilon_6 = 10^{b\cdot(6-a)} \quad (8)$$

Where ε_6 is the strain at one million cycles (see Figure 1.1). There is a discrepancy in the standard between the representation of the results as natural logarithm (ln) for 4PB-PR and Logarithm with base 10 (Log) for 2PB-PR. In this study, as the goal was to compare the two test methods, all fatigue lines have been calculated using Log as in equation (7). The initial complex stiffness modulus E^*_{100} (or $S_{mix,0}$ as defined by the standard) is measured after 100 load applications. The conventional criteria of failure (constant displacement amplitude) defined in the standard as fatigue life is the number of load applications, $N_{f/50}$, at which point the complex stiffness modulus has decreased to half its initial value.

2.1.1 Two-point bending test on trapezoidally shaped specimens (2PB-TR)

This method characterizes the behavior of bituminous mixtures under fatigue loading by 2-point-bending using trapezoidally shaped specimens. Each specimen is moved sinusoidally at its head by the imposed displacement amplitude until the failure criterion has been reached (*Table 2. 1*). The deformations shall be such that at least one third of the element tests provide results with $N \leq 10^6$ and at least one third of the tests provide results with $N \geq 10^6$. If this is not the case, additional element tests shall be carried out.

2.1.2 Four-point bending test on prismatically shaped specimens (4PB-PR)

This method characterizes the behavior of bituminous mixtures under fatigue loading in a four-point bending test equipment of which the inner and outer clamps are symmetrically attached to the slender rectangular shaped specimens (prismatic beams). The prismatic beam is subjected to four-point cyclic bending with free rotation and translation at all load and reaction points. The bending shall be realized by by applying the load with the inner clamps, in the vertical direction, perpendicular to the longitudinal axis of the beam. The vertical position of the end-bearings (outer clamps) is fixed. This load configuration creates a constant moment, and hence a constant strain, between the two inner clamps (*Table 2. 1*). The applied load is sinusoidal. During the test, the load, needed for the bending of the specimen, the deflection and the phase lag between these two signals is measured as a function of time. The fatigue characteristics of the material tested is determined from these measurements. For a given temperature and frequency, the test is undertaken at not less than three levels in the chosen loading mode (e.g. three strain levels with the constant deflection mode) with a minimum of six repetitions per level. The levels for the chosen loading mode are chosen in such a way that the fatigue lives (Nf/50) are within the range 10^4 to 2×10^6 cycles.

2.2 Bituminous mixtures - Test methods for hot mix asphalt – Part 26: Stiffness

[EN 12697-26:2012]

The European standards specify methods for characterizing the stiffness (i.e. complex modulus) of bituminous mixtures by alternative tests, including bending tests and direct and indirect tensile tests. The tests are performed on compacted bituminous mixtures under a sinusoidal loading or other controlled loading, using different types of specimens and supports. The procedure is used to rank bituminous mixtures on the basis of complex modulus, as a guide to rank relative performance of the pavement and for obtaining data for estimating the structural behavior in the road as well as test data according to specifications for bituminous mixtures. As these standards do not impose a particular type of testing device, the precise choice of the test conditions depends on the possibilities and the working range of the used device. This project has developed recommendations for testing various asphalt concrete mixes in Switzerland using the two point bending (2PB-TR) test on trapezoidal specimen and four point bending (4PB-PR) tests on prismatic specimens.

Suitably shaped samples, depending on the type of test, are deformed in their linear range, under repeated loads or controlled strain rate. The amplitudes of the stress and strain are measured, together with the phase difference between stress and strain.

Table 2. 1: Schematic diagram showing specimen type and loading condition for two point bending and four point bending tests [EN 12697-26]

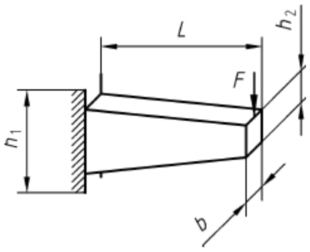
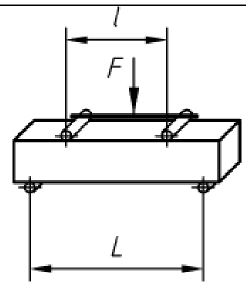
Type of loading	Designation	Schematic diagram
Two point bending test with trapezoidal specimen	2PB-TR	
Four point bending test with prismatic specimen	4PB-PR	

Table 2. 2 Form factor and mass factor for 2PB-TR and 4PB-PR for calculating E_1 and E_2 according to equations (5) and (6) [EN 12697-26]

Type of loading	Designation	Form factor γ	Mass factor, μ
Two point bending test with trapezoidal specimen	2PB-TR	$\frac{12L^3}{b(h_1-h_2)^3}\left[(2-\frac{h_2}{2h_1})\frac{h_2}{h1}-\frac{3}{2}-\ln\frac{h_2}{h_1}\right]$	0.135M+m
Four point bending test with prismatic specimen	4PB-PR	$\frac{L^2A}{bh^3}\left(\frac{3}{4}-\frac{A^2}{L^2}\right)$	$R(X)\left(\frac{M}{\pi^4}+\frac{m}{R(A)}\right)$

R(X) and R(A) depend on the location where the deformation is measured as defined in the standard. A=(L-l)/2, M and m are the Mass of specimen and mass of moving parts respectively.

3 Materials

In accordance to the project description two wearing courses, three binder courses and three base courses were selected from high performance Swiss motorways as shown in *Table 3. 1* and *Table 3.2*. The choice of specimen from pavement slabs as opposed to laboratory prepared samples was made in order to eliminate the effect of various compaction methods and to account for real performance oriented testing. However, it should be noted that this selection means that the samples were at various stages of aging and mechanical deterioration which has a direct effect on the obtained results.

According to the standards for 4PB specimens the base and height of the prismatic specimen should be 3 times the value of the maximum aggregate size, D. For D= 8, 11, 22, this would mean a minimum of 24, 33, 66 mm. Testing specimens larger than 50x50 mm was not possible due to the setup. Table *3. 1* lists the specimen dimensions. The material specifications are shown in *Table 3. 2*. The designations changed in 2005. Therefore the materials placed before this year also are shown with the old designation. According to the standard all surfaces should be cut and the sample should be sawed from the center of the slab allowing a 20mm border. In the case of the two wearing courses (C1 and D1) this condition was not met due to the limited layer thickness. An ideal solution would have been to follow the recommendation in the standard that if the thickness of the road layer is too small to meet the requirement with respect to the ratio between height H and the maximum grain size D (3 times), the beams shall be rotated over an angle of 90°. In such cases, the width B of the beam might not meet the requirement. The experience in this project confirms that it is important to have a height of at least 50 mm. Furthermore, the standard requires a minimum dimension of 40 mm for the 2PB tests.

The standard limits the tests for specimen with maximum aggregate size of up to 20 mm. This needs to be corrected as some European countries such as Switzerland have different sieve sizes that allow 22 mm aggregates. The tests performed in this project included samples with maximum aggregate size, D of 22 mm.

Table 3. 1 Specimen dimensions, mixtures and layer type. Designation in parenthesis is according to the standards when the layer was placed.

Type pavement	Layer	Mix Nr.	Depth [mm]	D [mm]	Specimen Dimensions [mm] 2PB	4PB
Wearing course	SMA11	C1	40	11	56x25x25x250	40x40x450
	AC MR 8	D1	30	8	56x25x25x250	30x30x450
Binder course	AC B 22H	B2	90	22	70x25x25x250	50x50x450
	AC B 22 S (HMT 22 S)	C2	90	22	70x25x25x250	50x50x450
	AC B 22S	D2	70	22	70x25x25x250	N/A
Base course	AC T 22 H	B3	70	22	70x25x25x250	50x50x450
	AC EME 22 (BBHM 22)	F3	80	22	70x25x25x250	50x50x440
	AC T 22 S (HMT 22 S)	G3	80	22	70x25x25x250	N/A

Table 3. 2 type of mixture, binder type, air void content, binder content of cores, richness modulus, characteristics of the recovered binder (NN=Not known, sd=standard deviation, NA=not applicable)

Designation	C1	D1	B2	C2	B3	F3	D2*	G3*
Section	A3 Aargau	Bern	A2 Bellinzona sud – Bellinzona nord	A3 Aargau	A2 Bellinzona sud – Bellinzona nord	A1 Yver-don-Bern – Tronçon Arrissoules	N1 05 Aargau	A1 Payerne-Avenches
Type (new des.)	SMA 11	AC MR 8	AC B 22 H	AC B 22 S	AC T 22 H	AC EME 22	AC B 22 S	AC T 22 S
Type (old des.)	SMA 11	NA	NA	HMT 22 S	NA	BBHM 22	NA	HMT 22 S
Binder Type	NN	NN	PmB C 30/50-58	NN	NN	B 10/20	NN	B 55/70
Layer	Wearing 1	Wearing 2	Binder 1	Binder 2	Base 1	Base 2	Base3	Base 4
Laying year	1998	2008	2007	1998	2007	1999	2008	1995
Sampling year	2009	2009	2009	2009	2009	2009	2009	2009
Years in service	11	1	2	11	2	10	1	14
Sieve Size [mm]	% Passing (by Mass)							
31.5	-	-	100.0	100.0	-	100.0	100.0	-
22.4	-	-	96.5	97.0	100.0	98.9	98.8	100.0
16	100.0	100.0	84.9	90.5	91.7	83.1	86.6	91.2
11.2	95.6	99.3	70.3	76.8	77.6	71.2	72.9	73.9
8	65.0	94.5	60.0	66.1	66.4	58.9	61.6	60.6
5.6	37.9	64.6	50.2	53.3	56.2	48.1	51.6	49.5
4	32.1	37.1	42.5	43.5	48.4	40.2	43.5	44.3
2	25.7	24.3	31.5	30.9	34.9	28.9	29.6	29.4
1	20.6	18.8	26.0	22.1	29.7	23.5	21.1	20.6
0.5	17.5	15.5	16.7	16.5	17.6	15.0	16.0	15.4
0.25	15.1	12.6	13.1	12.8	11.8	11.6	12.2	12.0
0.125	12.8	10.3	10.2	10.2	7.8	9.0	9.3	9.4
0.063	10.5	7.9	7.8	7.8	5.3	6.8	7.1	7.3
Binder [% by wght. of total mix]	6.88	5.69	4.65	4.58	4.53	5.17	4.34	4.26
Richness modulus M_R [-] (1)	4.24	3.62	2.94	2.90	3.06	3.40	2.78	2.71
Voids cores [% by vol.] (2)	4.1 (sd 0.81)	8.5 (sd 0.73)	3.5 (sd 0.92)	3.2 (sd 0.76)	9.2 (sd 1.55)	8.9 (sd 2.50)	1.5 (sd 0.66)	4.5 (sd 0.73)
Bitumen recovery of sample								
Penetration 25°C [0.1mm]	43	40	30	45	7	9	34	31
R&B [°C]	54.5	70.0	68.8	57.9	81.6	81.7	67.7	64.8
IP [-]	-0.5	2.3	1.4	0.3	0.6	1.0	1.5	0.8

(1) Calculated based on SN EN 640 431-1b-NA
(2) Standard deviation based on 26 or 32 samples

4 Experimental Program

Two laboratories were involved in performing the experiments. Empa has used the four point bending (4PB-PR) and LAVOC the two point bending (2PB-TR) tests. Empa has used a state of the art equipment that was specifically purchased in view of this project. The setup includes a novel clamping system that was designed to account for relaxation in the beam.

Table 4. 1 shows the experimental program including the number of mixtures, number of specimens, type of tests and test conditions for stiffness as well as fatigue tests. The experimental setup for the 4PB-PR tests is shown schematically in Figure 4. 1. Figure 4. 2 shows the four clamps (a), specimen clamped (b) one AC EME 22 Base course specimen and 18 specimen with dimensions 50*50*440 mm tested for each mixture (c).

The experimental setup for 2PB-TR is shown in *Figure 4. 3* (a) and (b). The samples are shown in Figure 4. 3 (c) and the failed samples in Figure 4. 3 (d).

Table 4. 1 Experimental program, where, 4PB=4 point bending beam, 2PB=2 point bending beam, WC: wearing course, BC: binder course. (*) one set of tests was done at 10°C, 10Hz

Lab	Empa	LAVOC	Notes
Number of Mixture	6	8	2 WC + 3 BC + 3 Base
Number of Samples	18	18	4 Modulus+ Fatigue 14 Fatigue
Test Type	4PB-PR	2PB-TR	European Standard Tests
Test Conditions (Complex modulus test)	10, 15, 20 °C 3, 10, 25 Hz	10, 15, 20 °C 3, 10, 25 Hz	4 replicates
Test Conditions (Fatigue Test)	20 °C, 10°C (*) 25 Hz, 10 Hz (*)	10 °C 25 Hz	6 replicates with 3 strain levels

In the 4PB-PR tests the complex modulus is calculated from the measured force and relative deflection between the center inductive deformation sensor (LVDT) and a second one under the support (Figure 4. 1) using the equations provided in the EN standards. Sampling takes place after the first 100 cycles until the last cycle (nr 200). For every cycle 50 values are recorded for the time difference between two following time t values:

$$\Delta t = \frac{1}{50 \cdot f} \tag{9}$$

where f is the frequency. For calculating the complex stiffness modulus, only the last 3 cycles are taken into account.

In the 2PB test, the modulus calculation is achieved through the following steps: Force and displacement signals are recorded in 1 second intervals. Sampling rate is adapted to measurement frequency. Both signals are analyzed with an algorithm to extract their amplitudes and their phase difference (Labview's software signal processing algorithm). The values of amplitudes (force and displacement) as well as the phase angle are filtered with the calculation of a moving average of n previous values. The n-value is determined by the operator (usually n = 20). The final measurement values are noted generally 45 seconds to 1 minute after setting the test conditions. This delay meets the stabilization time recommended by the EN 12697-26:2004 standard (30 seconds to 2 minutes) and is sufficient to fill entirely the moving average buffer with values corresponding to the measurement steady state.

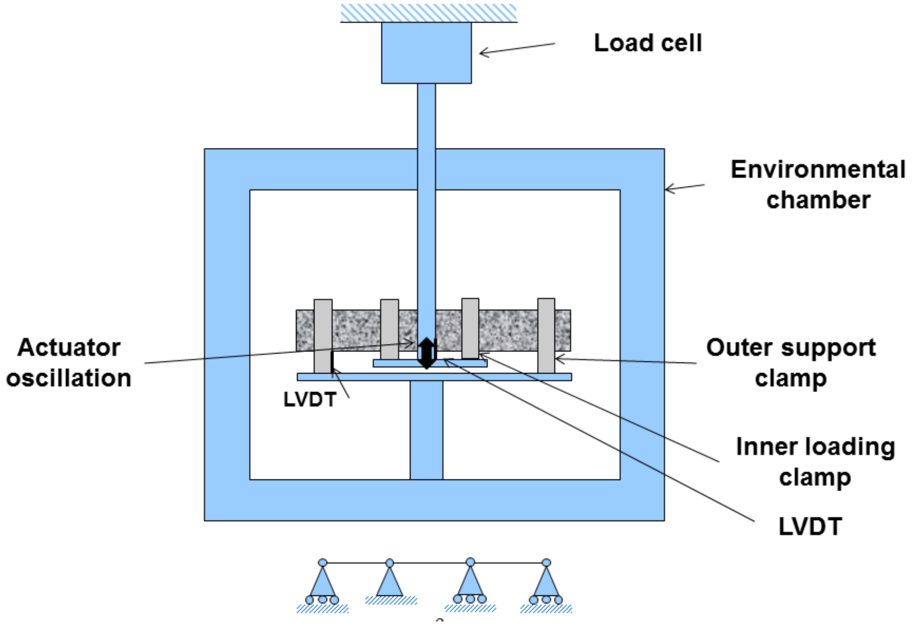


Figure 4. 1 Experimental set up of the 4PB test

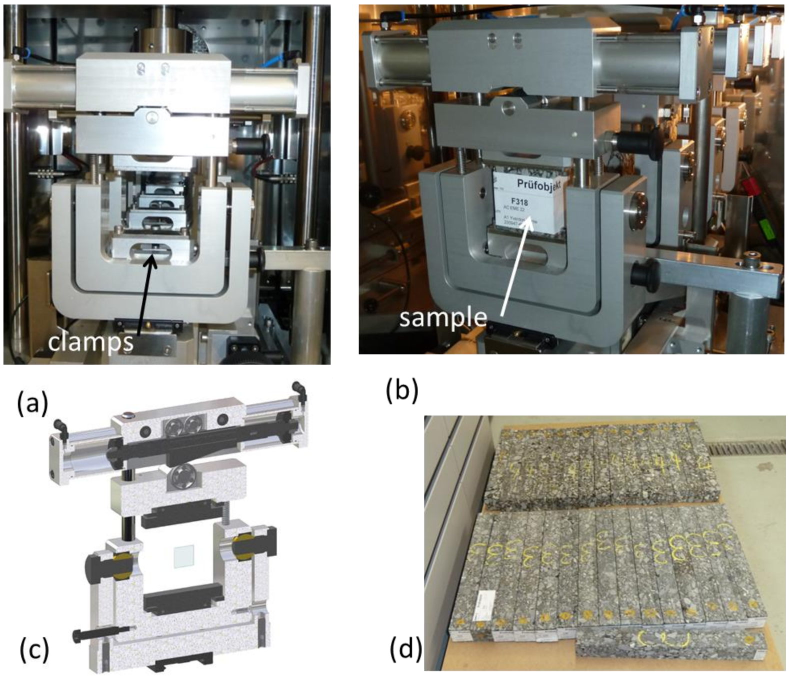


*Figure 4. 2 Experimental set up showing: (a) the four clamps; (b) specimen clamped; (c) The specially designed pneumatic clamp, (d)18 specimen with dimensions 50*50*440mm tested for each mixture*

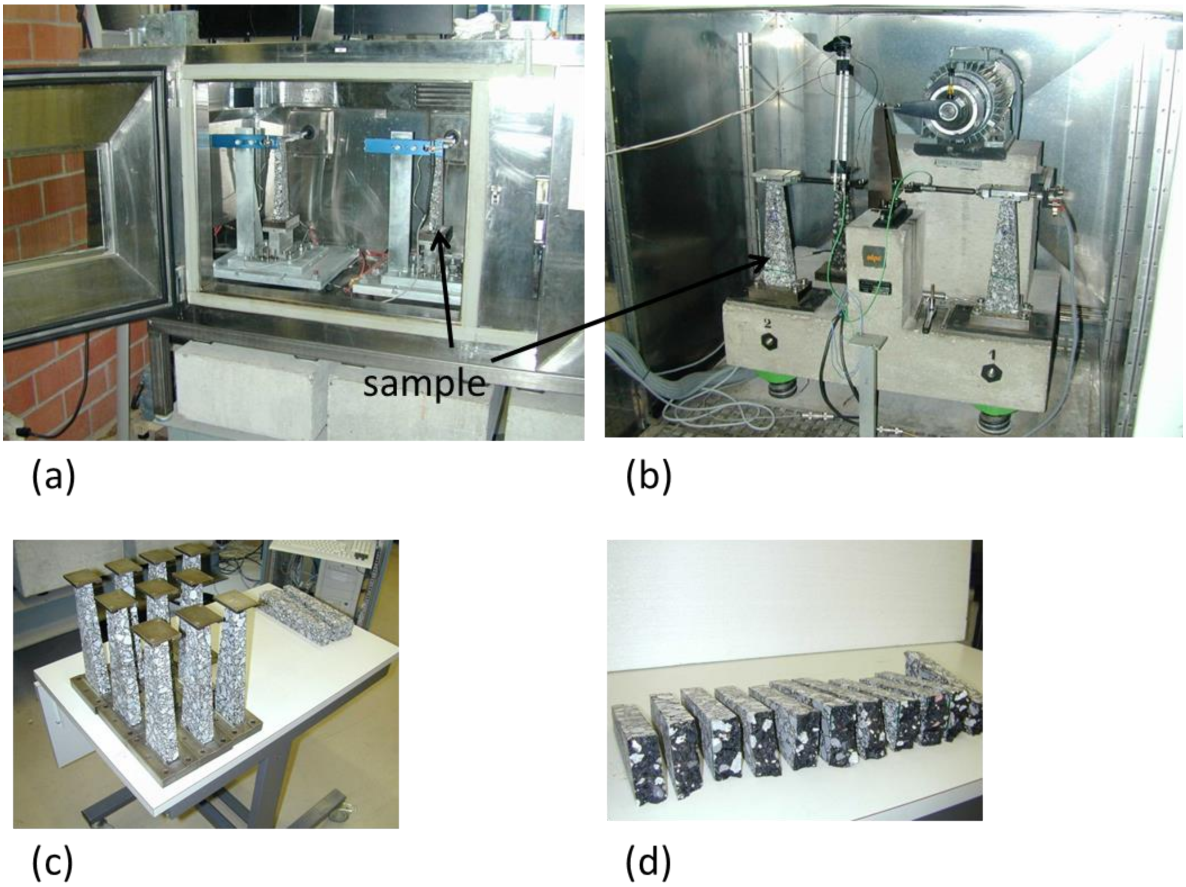


*Figure 4. 3 Experimental set up for: (a) 2PB complex modulus test; (b), fatigue tests; (c) trapezoidal sample with dimensions 25 * 25 (56) * 250mm; (d), specimens after fatigue testing*

5 Experimental Results

Following the experimental program listed in chapter 4 tests were performed using the 2PB-TR and 4PB- PR setup. A total of 252 (2*18*6+2*18) tests were performed.

The following factors can affect the results:

- Bulk density of the sample can affect the fatigue life. However, as shown in the example of Figure 5. 1, in these series of tests the effect of bulk density on fatigue life could not be established as other factors such as inhomogeneity of samples play a greater role.
- Higher maximum aggregate size results in a more heterogeneous structure and can theoretically result in more scatter in the results in general. However, the experimental results from this project indicate that the effect of aggregate size could not be isolated as shown in Figure 5. 19 where the materials with 11 and 8 mm maximum aggregate size do not show less scatter in the results. This is true for 2PB as well as 4PB.
- Micro structure of the sample under the load or support location can affect the results. When a damaged aggregate is directly under the support, the sample may fail at this location earlier.

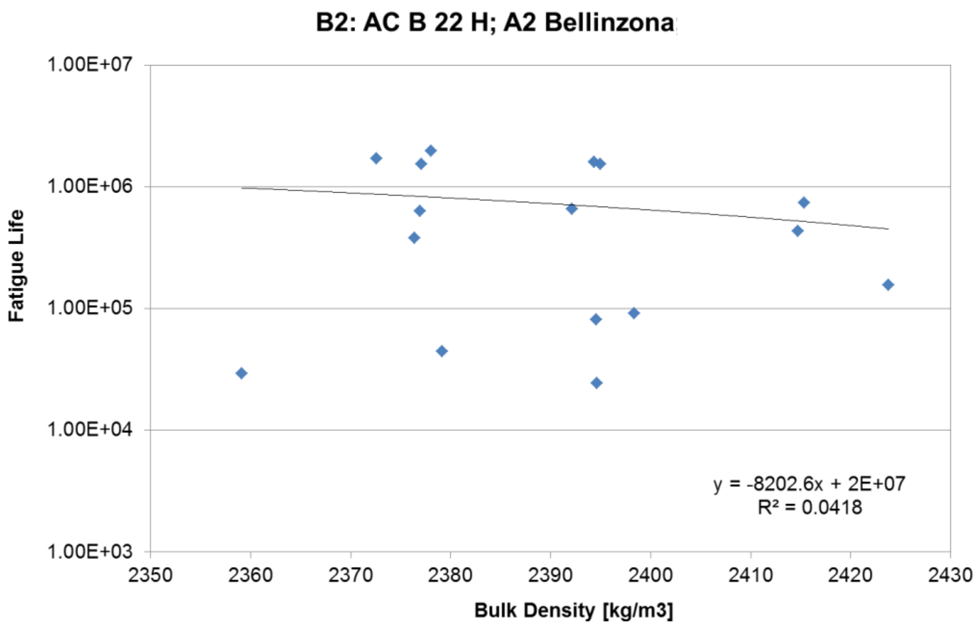


Figure 5. 1 Bulk density vs. fatigue life (Nf/50) for AC B 22 H (B2)

5.1 Complex stiffness modulus and phase angle

Complex modulus (stiffness) and phase angle were determined at the 100th cycle as prescribed by the standard and at 10, 15 and 20°C each at 3, 10 and 25 Hz. The values presented are averages of 4 specimens as also prescribed by the European standards.

The results presented in Figure 5. 3 to Figure 5. 34 indicate that complex modulus values of 4PB are consistently higher than for 2PB tests. This is in line with international studies as discussed and shown in Table 1. 3. The Rilem study indicated a maximum difference of 17 % in complex modulus and -24% in phase angle between the 2PB and 4PB tests. Furthermore, the Rilem study was carried out on laboratory compacted specimens, resulting in more homogeneous samples than the field samples used in the current study.

As shown in Figure 5. 2 the 4PB and 2PB tests result in different stress states in the material. Therefore it is not expected to achieve the same results from the two tests. As demonstrated in Figure 5. 2 the 4PB tests exposes a larger area of the material i.e between the supports to fatigue loading, shown in red, and can therefore identify weak positions better than the 2PB test where a smaller area is loaded. An additional effect is the mass affecting inertia in dynamic measurements as the two tests use different size samples with different masses. The 2PB-TR specimens are glued whereas the 4PB-PR specimen are clamped and this also has an effect on the results. Nevertheless, as shown in Figure 5. 21 and Figure 5. 22, for all data there is a good relationship between the 4PB and the 2PB results. The regression is shown in equation (10) for the complex stiffness modulus and (11) for phase angle:

$$E^*_{100,4PB} = 1.081\ E^*_{100,2PB} \quad (R^2 = 0.84) \tag{10}$$

$$\Phi_{100,\ 4PB} = 1.31\ \Phi_{100,\ 2PB} \quad (R^2 = 0.76) \tag{11}$$

Furthermore, Figure 5. 23 and Figure 5. 25 show the regression for all AC 22 layers. As seen in these figures a correlation coefficient R^2 of 0.91 and 0.92 exists for both complex modulus and phase angle that indicate better agreement between 4PB and 2PB results for all AC 22 layers. Similarly, the regression of other materials, i.e. SMA, AC MR and AC EME is shown in Figure 5. 24 and Figure 5. 26. As seen in these figures, the correlation coefficient here is lower with 0.90 and 0.76 for complex modulus and phase angle respectively.

An overall impression can be obtained from Figure 5. 19. This figure shows all the materials tested at 15°C and 10Hz as required by the Swiss annex to the standard. As seen, the scatter in the results (for 4PB-PR) as well as difference between 2PB and 4PB was higher for AC MR8 and AC EME 22. AC MR 8 samples used in 4PB tests were the thinnest tested (30x30mm) with a rough surface. This sample size and the rough surface discussed below had an effect in the 4PB results as the sample mass was, as a result, too small and the effect higher especially at 25Hz (Figure 5. 5 and Figure 5. 6). The sample size of the 2PB-TR specimen was also limited 25x25 due to the layer thickness. Also, in this case, it was not possible to cut the top 20 mm. In general, as shown in Figure 5. 19, the scatter in the results is higher for 4PB-PR than 2PB-PR. In addition, the 4PB complex modulus results at 25 Hz are below expected values and the phase angle at 25 Hz are above expected values. This can be attributed to the shape of the sine curve for the applied force as at this frequency disturbance occurs in the sine curve and mathematical compensation can miss the peaks. This is demonstrated in the examples in Figure 5. 3 to Figure 5. 20.The fact that the results at 25 Hz were independent of temperature shows that the origin of this problem is not due to the setup. The results look better in case of materials with higher complex moduli (i.e.>10000 MPa).

Presentation of the results in terms of Black diagrams (IE*I vs. ϕ) allow elimination of the temperature factor and calculation of the elastic modulus at zero phase angle. Table 5. 1 summarizes the results of the Black diagrams. It can be seen that the pure elastic modulus obtained from 2PB and 4PB tests are not equal in most cases. The difference is between zero and 36%. However the slopes in the Black diagrams, i.e the relationships between complex modulus IE*I and phase angle ϕ, are similar.

Due to size limitations the two wearing courses C1 and D1 were not cut on the surface as required by the standards. This uncut surface has a negative effect on the results as it introduces more inhomogeneity and cracks as can be seen in more scatter in the results in Figure 5. 3 to Figure 5. 6. This is especially noticeable at 25Hz and in the phase angle values. On the other hand it reflects performance in a realistic way.

As shown in Figure 5. 19 and Figure 5. 20, the results from 2PB tests for D2 and G3 were very similar to those obtained for other AC B 22 materials. Therefore further 4PB tests were not done on these materials.

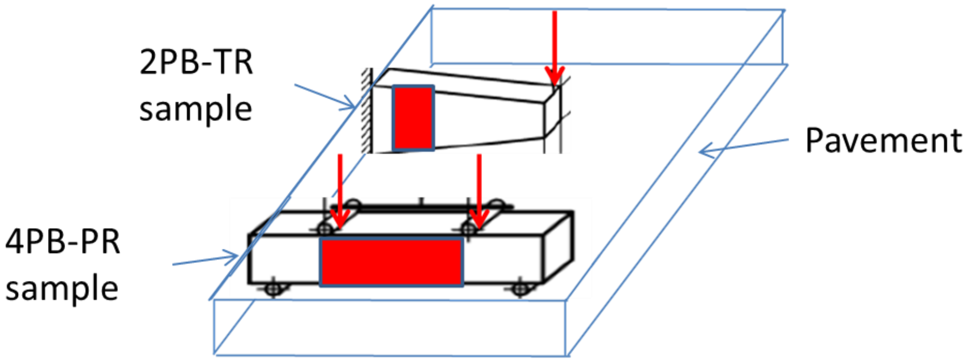


Figure 5. 2 The 2PB-TR and 4PB-PR specimens shown within the pavement. The tests create different stress states in the material, therefore leading to different results. 4PB-PR tests allow more area of the sample (shown in red) under high stress fatigue loading, i.e. between the loading points, as compared to 2PB-TR.

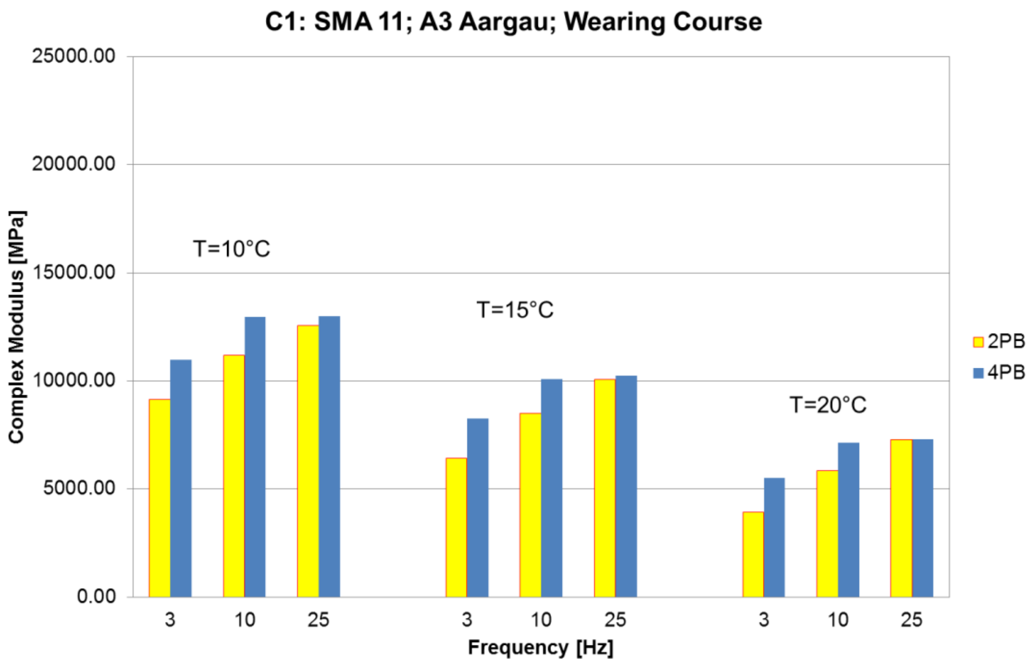


Figure 5. 3 Initial complex stiffness modulus, $E^*_{100,}$ values obtained from two point bending and four point bending for SMA 11 (average of 4 samples)

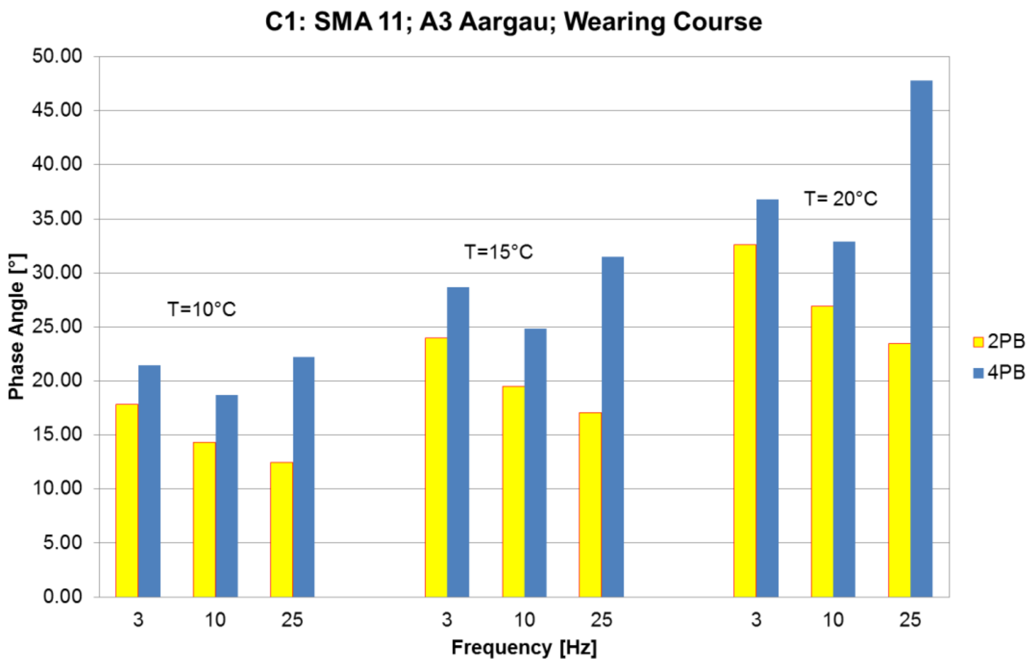


Figure 5. 4 Initial phase angle, $\Phi_{100,}$ values obtained from two point bending and four point bending for SMA 11 (average of 4 samples)

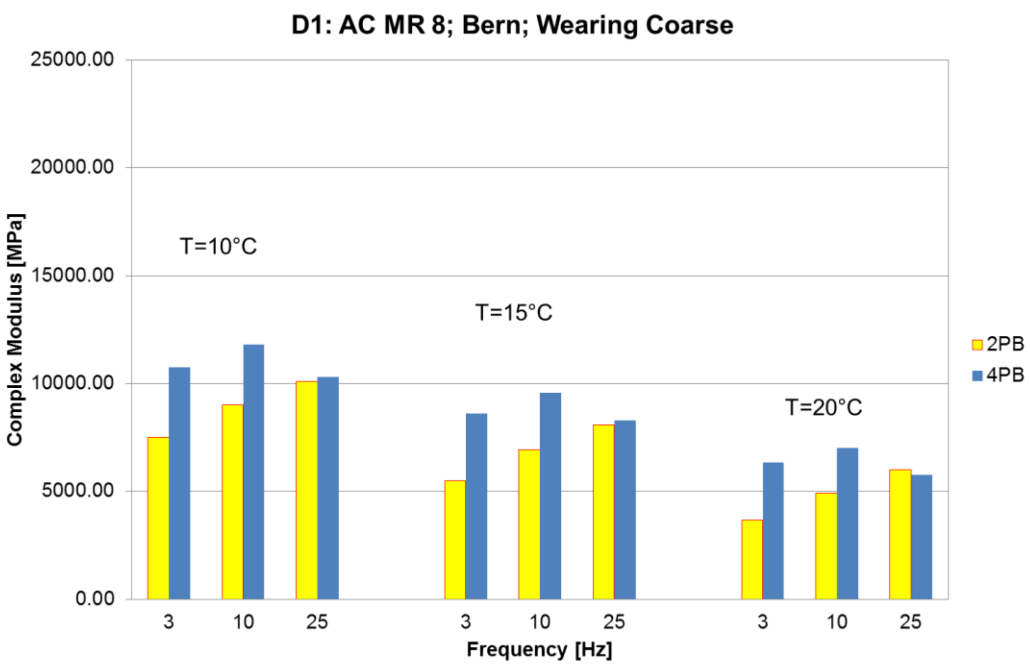


Figure 5. 5 Initial complex stiffness modulus, $E^*_{100,}$ values obtained from two point bending and four point bending for AC MR 8 (average of 4 samples)

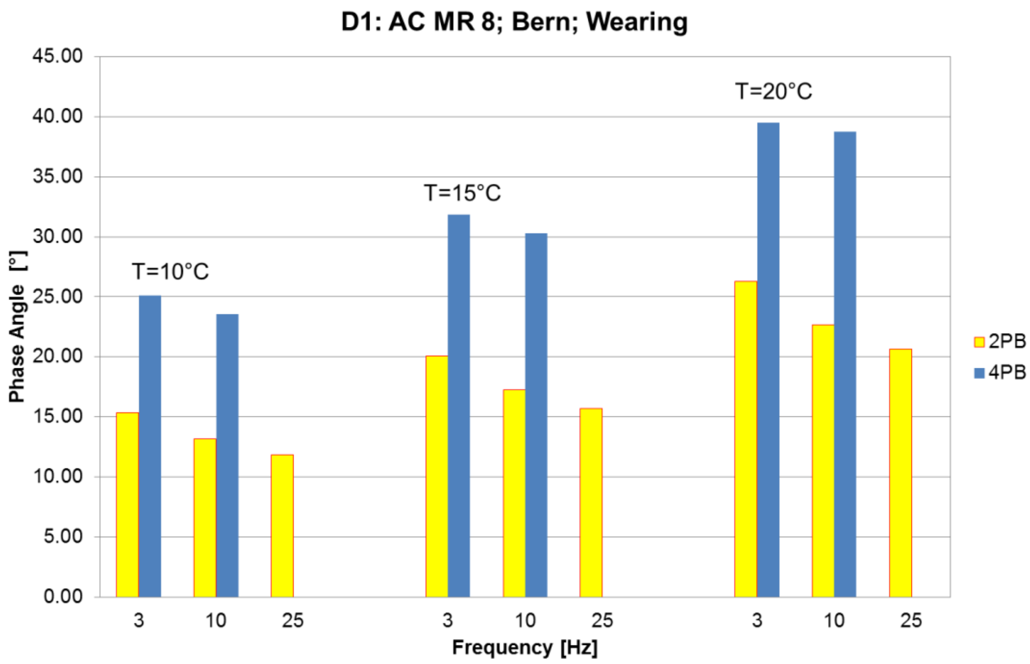


Figure 5. 6 Initial phase , $\Phi_{100,}$ angle values obtained from two point bending and four point bending for AC MR 8 (average of 4 samples). At 25 Hz 4PB values were not valid

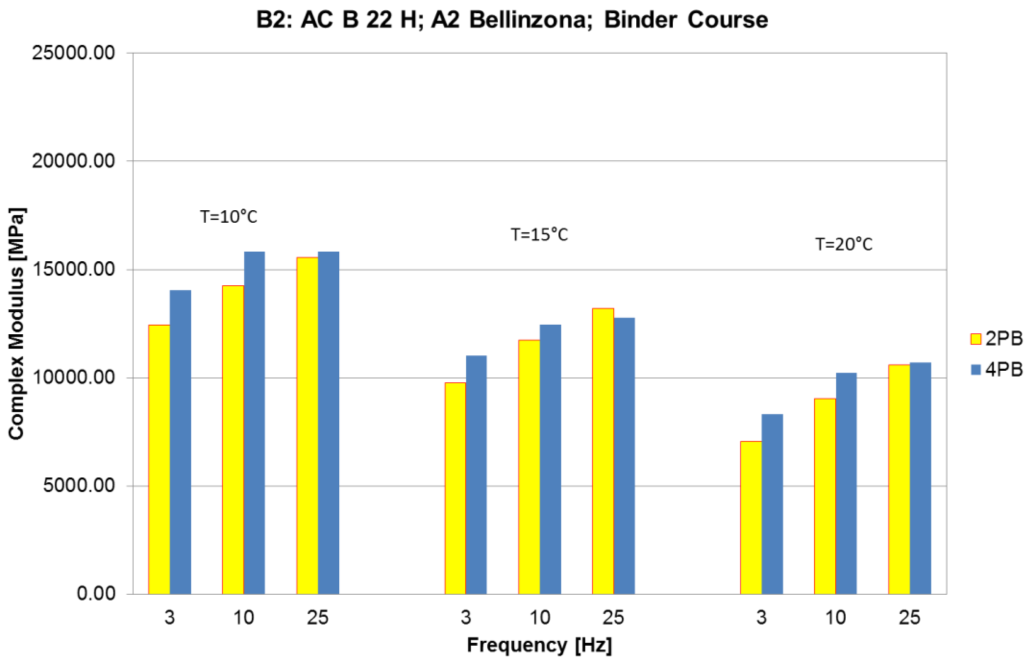


Figure 5. 7 Initial complex modulus , $E^*_{100,}$ values obtained from two point bending and four point bending for AC B 22 H (average of 4 samples)

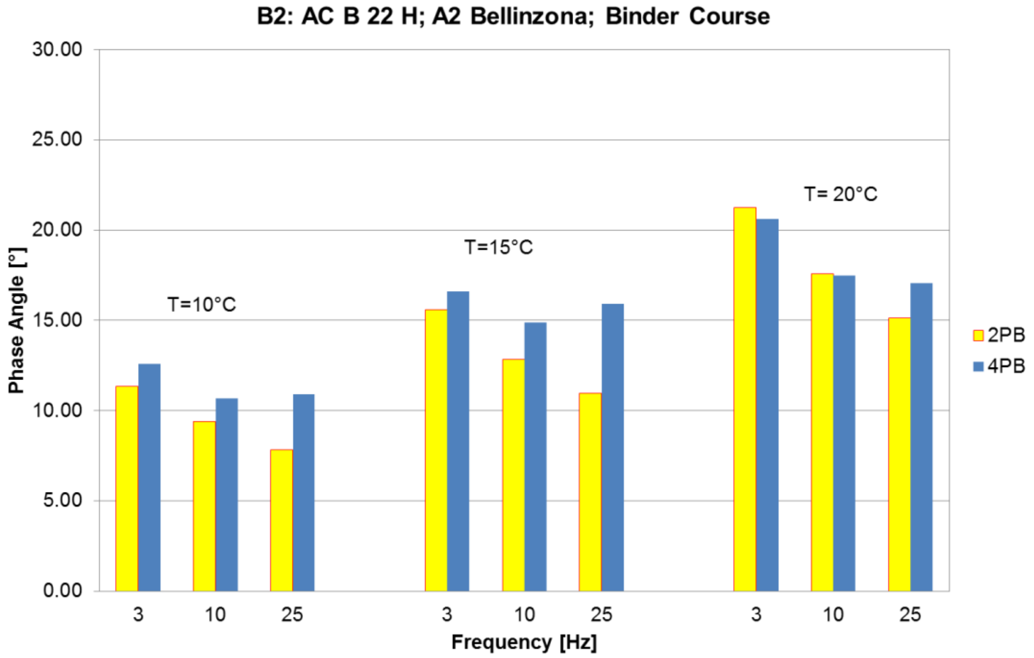


Figure 5. 8 Initial phase angle, $\Phi_{100,}$ values obtained from two point bending and four point bending AC B 22 H (average of 4 samples)

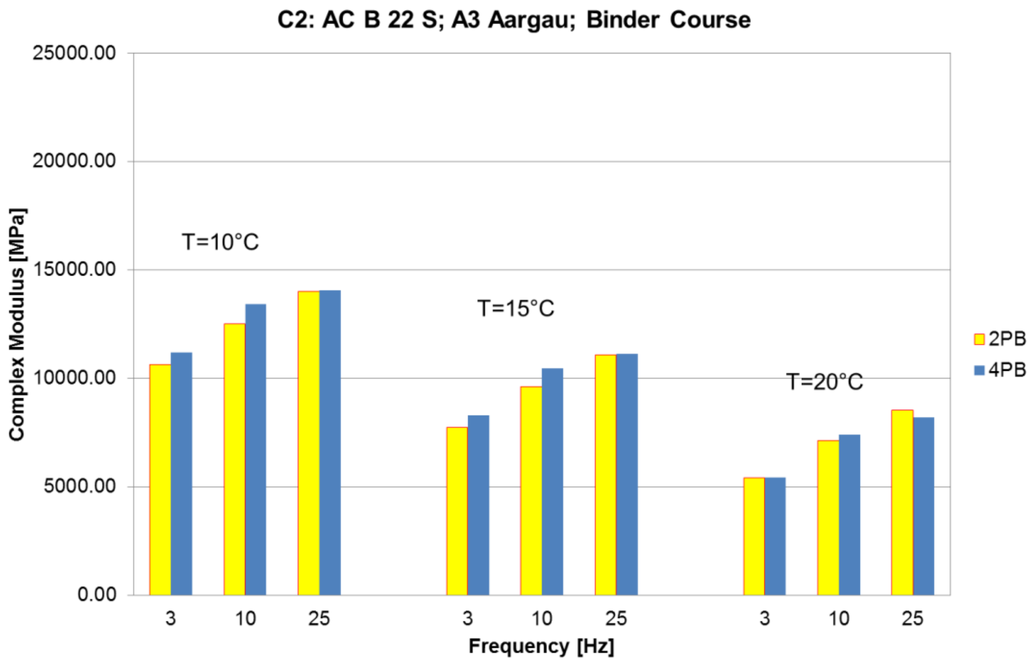


Figure 5. 9 Initial complex modulus , $E^*_{100,}$ values obtained from two point bending and four point bending for AC 22 (average of 4 samples

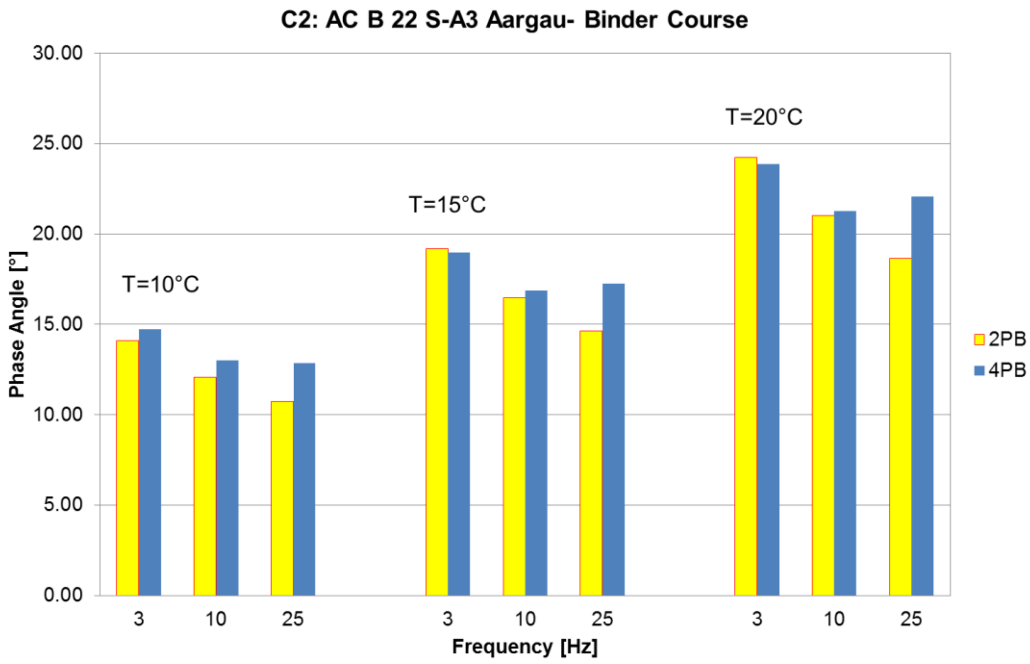


Figure 5. 10 Initial phase angle , $\Phi_{100,}$ values obtained from two point bending and four point bending for AC B 22 S (average of 4 samples)

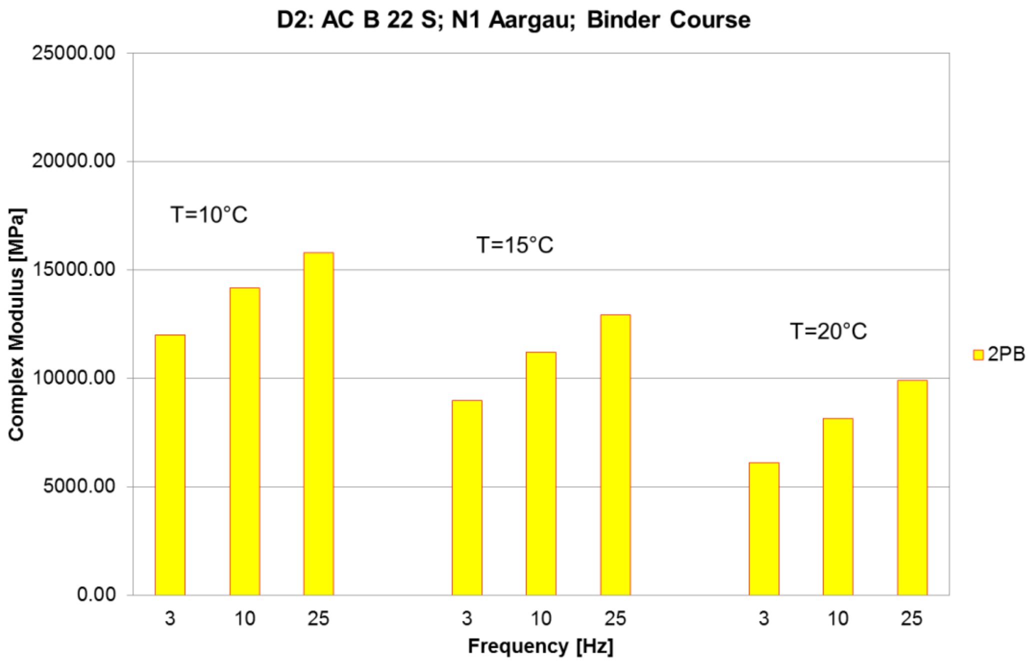


Figure 5. 11 initial complex modulus , $E^*_{100,}$ values obtained from two point bending for AC B 22 S (average of 4 samples)

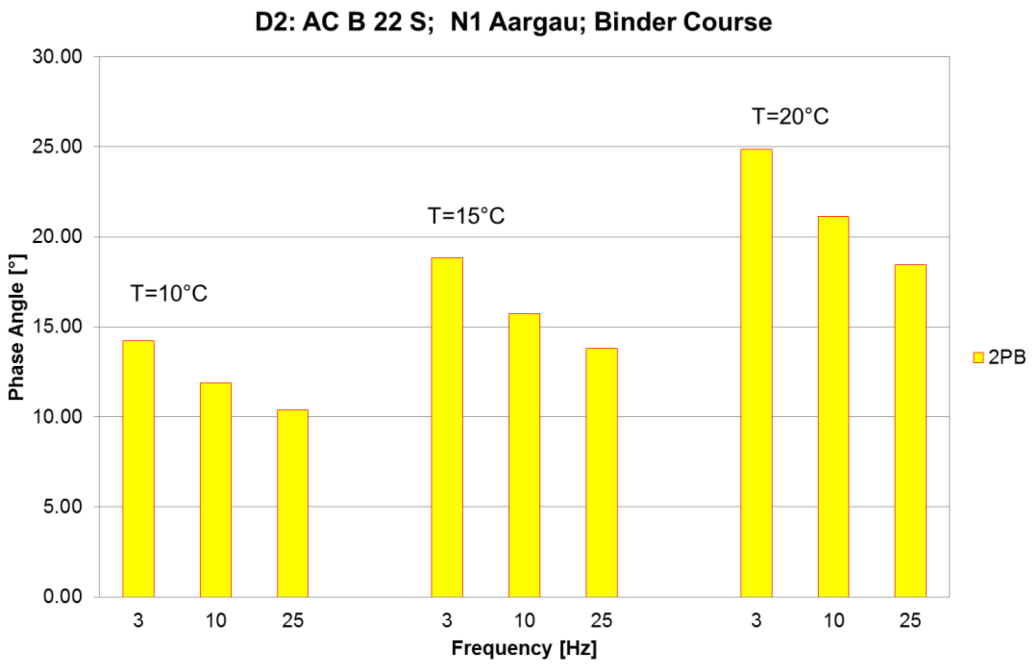


Figure 5. 12 Initial phase angle, $\Phi_{100,}$ values obtained from two point bending for AC B 22 S (average of 4 samples)

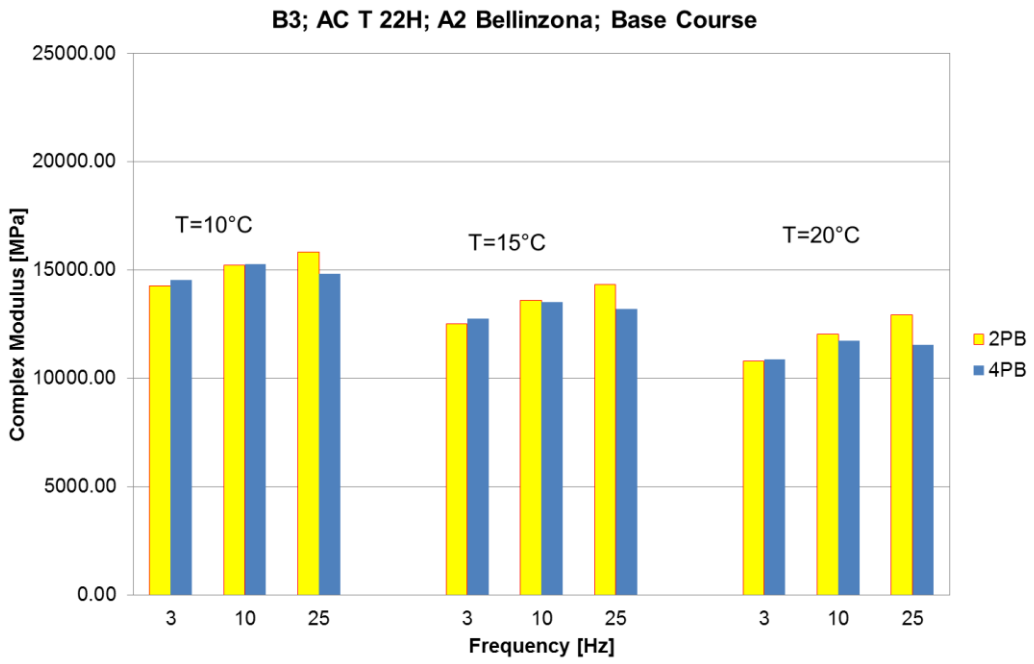


Figure 5. 13 initial complex modulus , $E^*_{100,}$ values obtained from two point bending and four point bending for AC T 22 H (average of 4 samples)

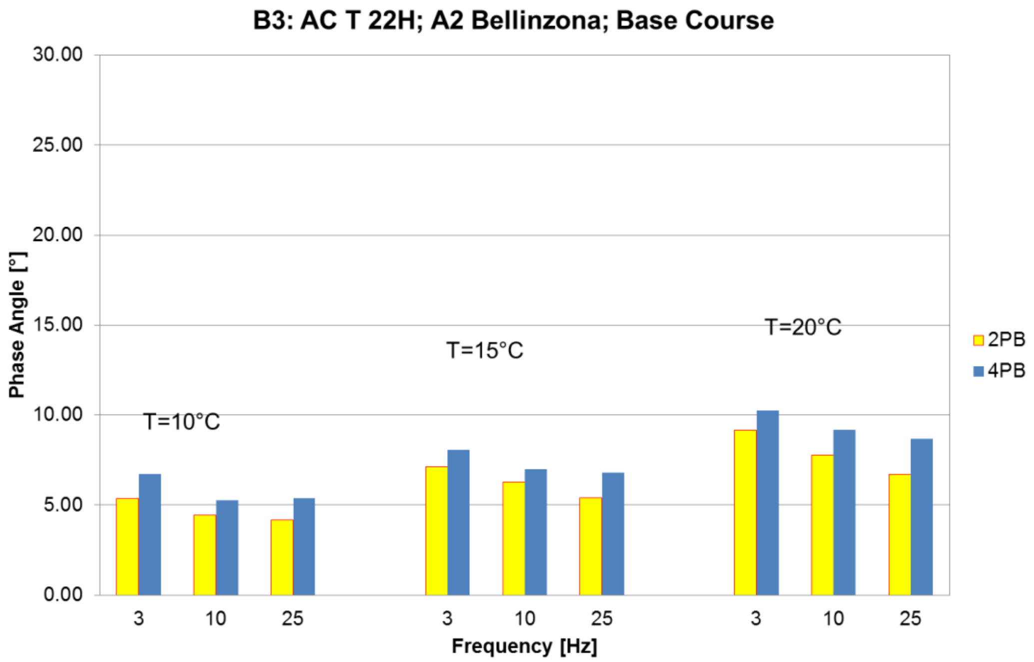


Figure 5. 14 Initial phase angle , $\Phi_{100,}$ values obtained from two point bending and four point bending for AC T 22 H (average of 4 samples)

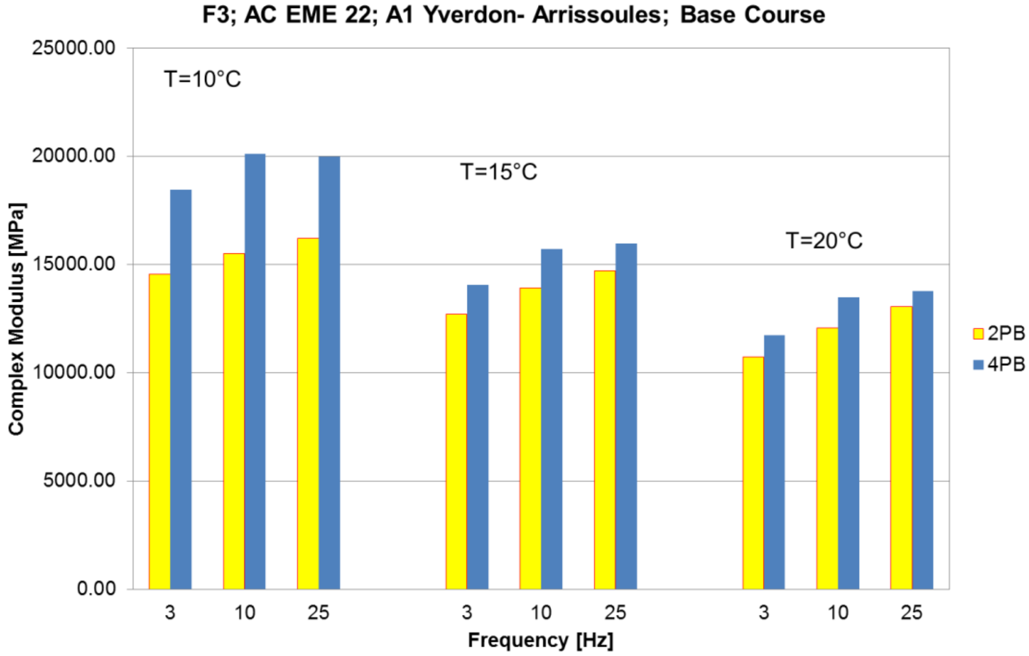


*Figure 5. 15 initial complex modulus , E*100, values obtained from two point bending and four point bending for AC EME 22 (average of 4 samples)*

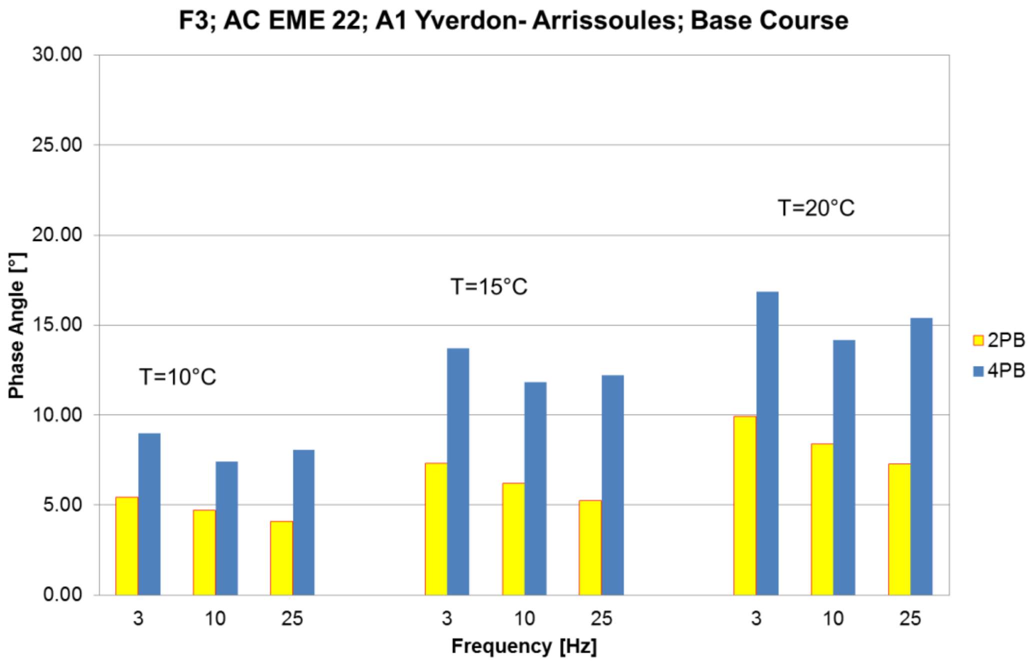


Figure 5. 16 initial phase angle , Φ100, values obtained from two point bending and four point bending for AC EME 22 (average of 4 samples)

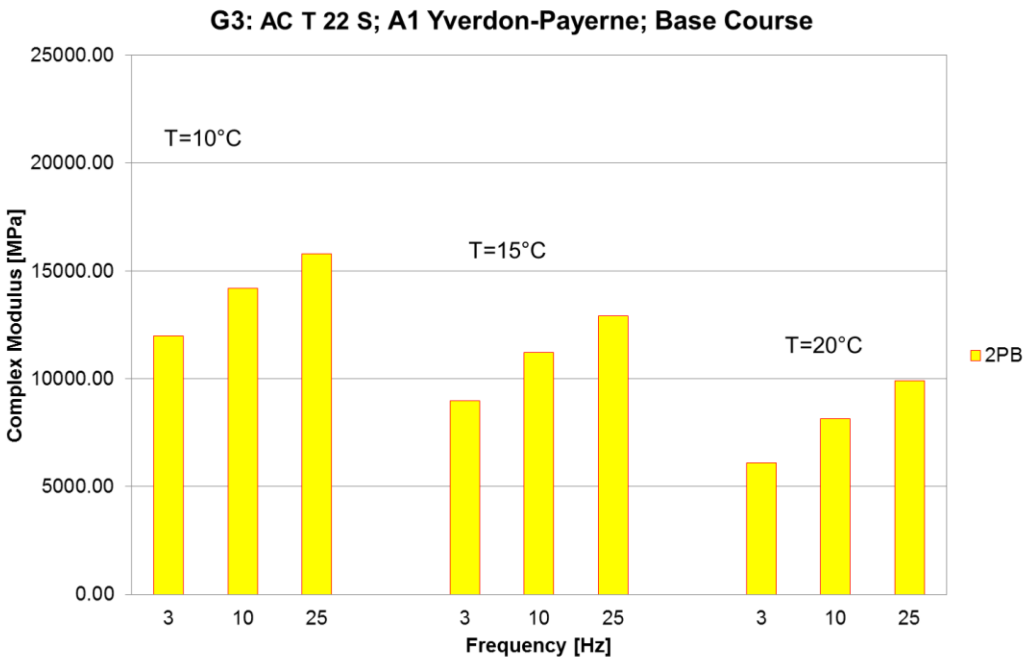


Figure 5. 17 Initial complex modulus , $E^*_{100,}$ values obtained from two point bending for AC T 22 S (average of 4 samples)

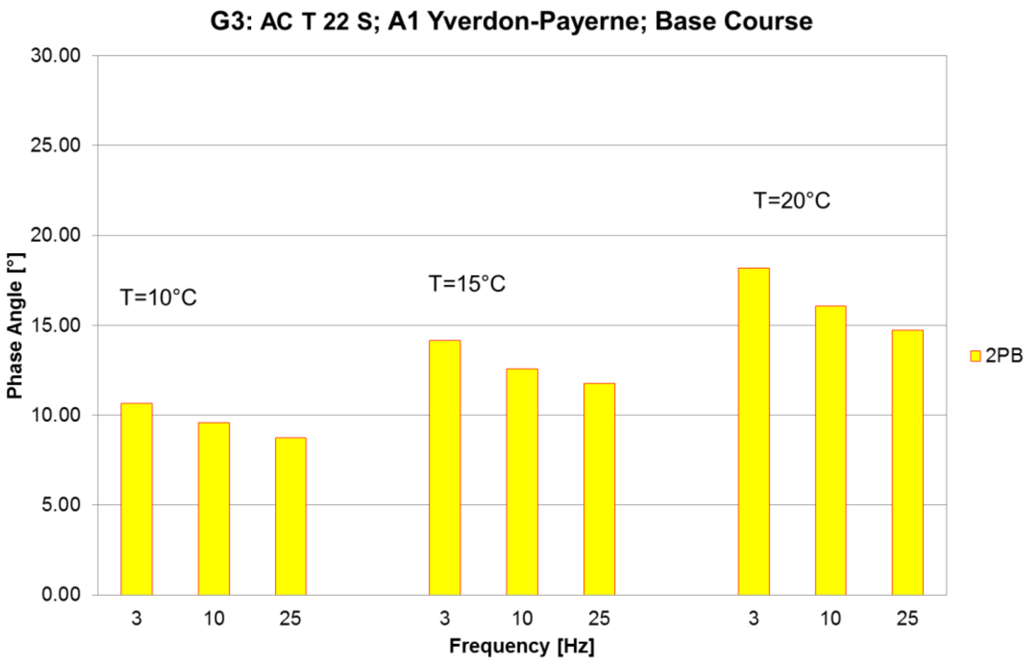


Figure 5. 18 initial phase angle , $\Phi_{100,}$ values obtained from two point bending AC T 22 S (average of 4 samples)

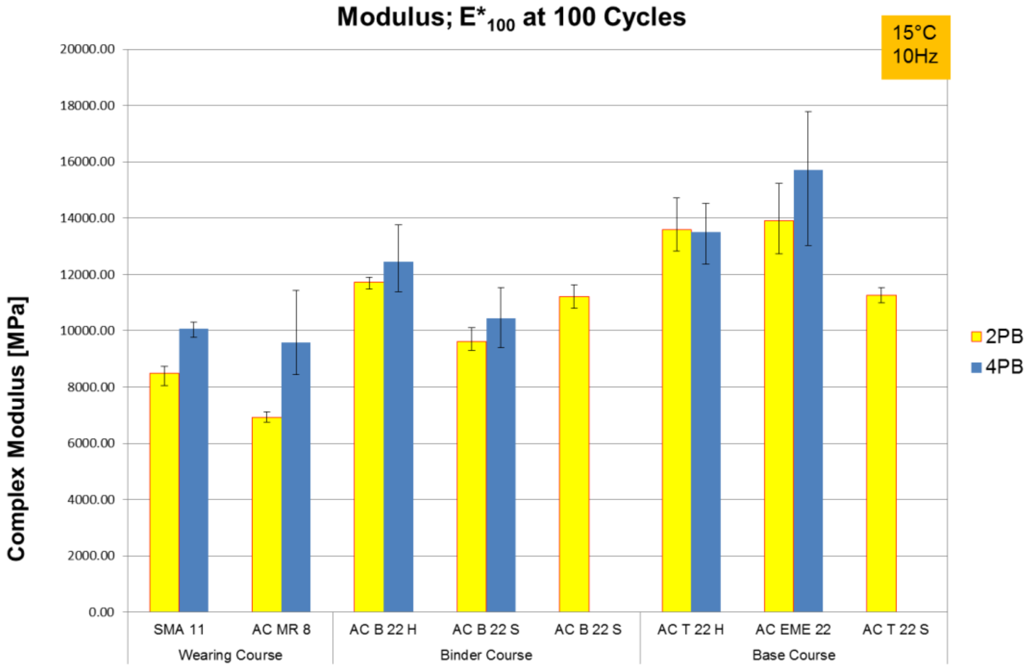


Figure 5. 19 Initial complex modulus values , $E^*_{100,}$ of all the materials tested at 15°C and 10 Hz as required by the Swiss annex to the standard

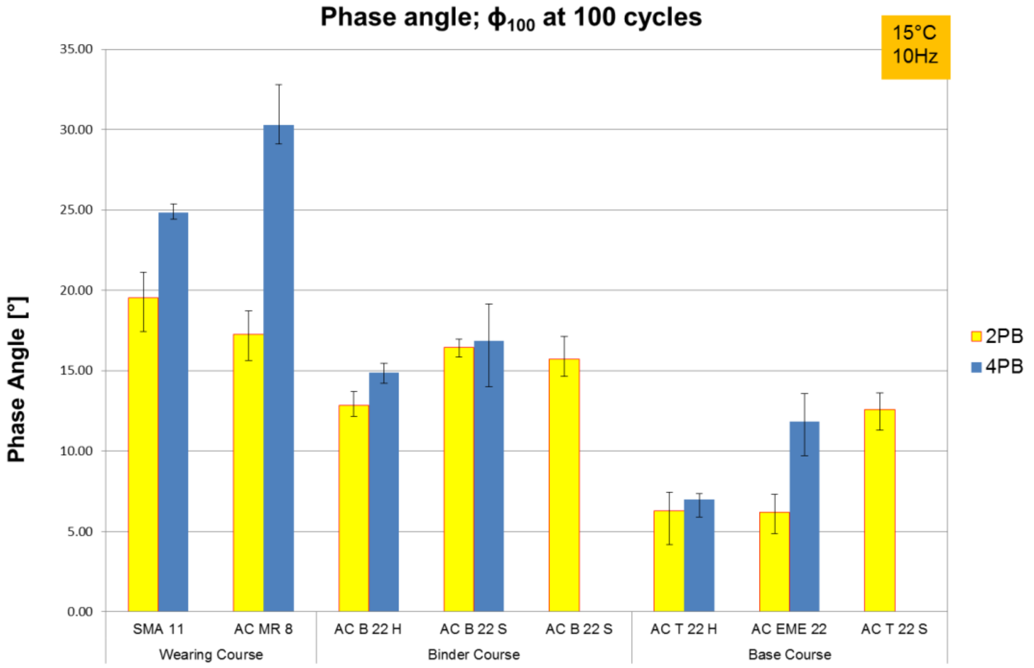


Figure 5. 20 Phase angle, $\Phi_{100,}$ of all the materials tested at 15°C and 10 Hz as required by the Swiss annex to the standard

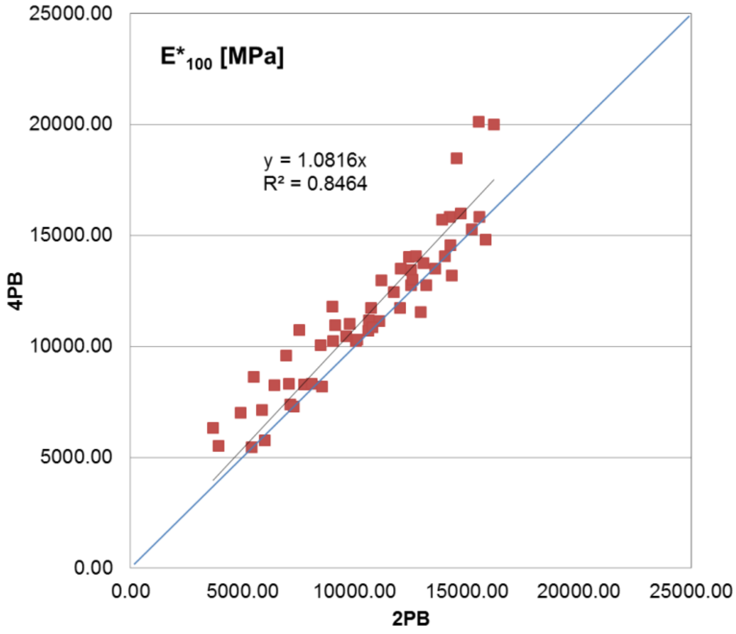


Figure 5. 21 Regression of initial complex modulus, $E^*_{100,}$ between 4PB and 2PB tests for all data (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

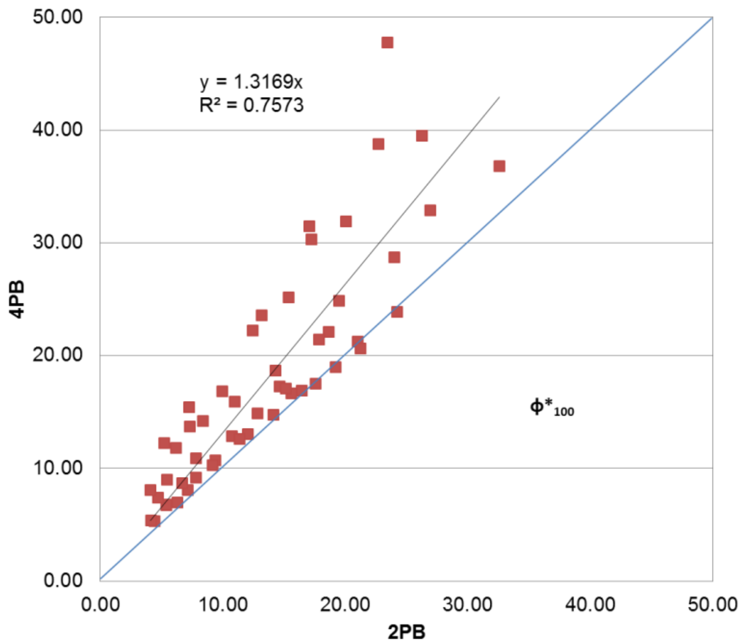


Figure 5. 22 Regression of initial phase angle, ϕ^*_{100} between 4PB and 2PB test for all data (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

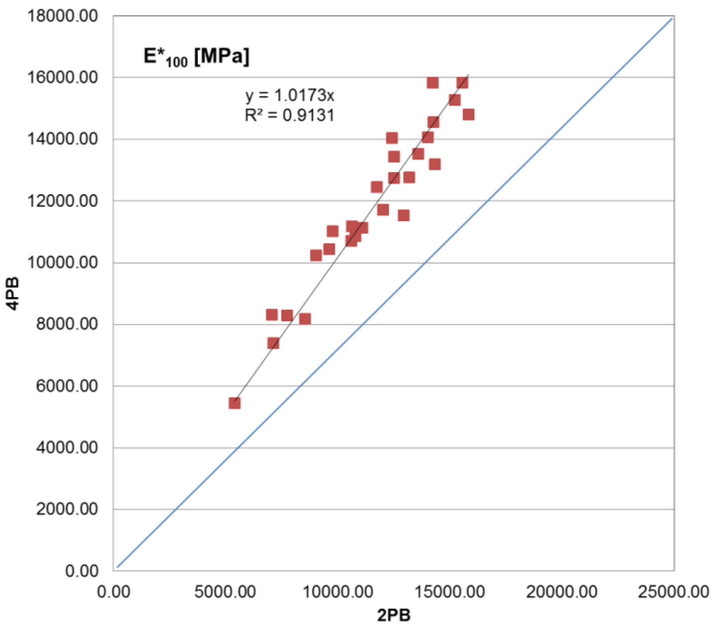


Figure 5. 23 Regression of initial complex modulus, $E^*_{100,}$ between 4PB and 2PB tests for AC B 22 H, AC B 22 S, AC T 22 H (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

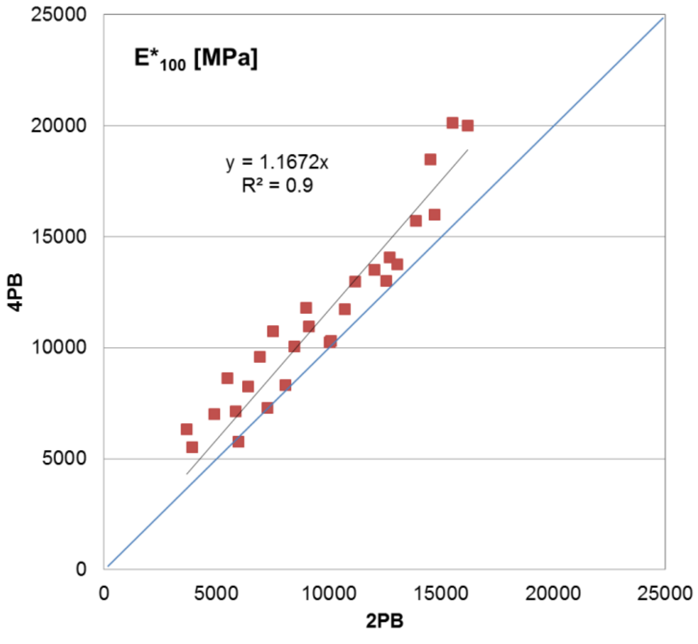


Figure 5. 24 Regression of initial complex modulus, $E^*_{100,}$ between 4PB and 2PB tests for AC EME 22, SMA11 and AC MR 8 (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

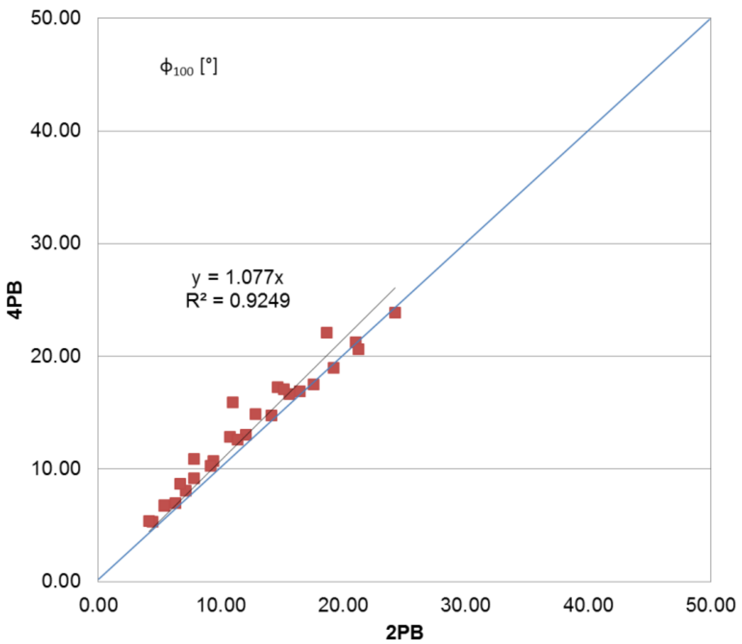


Figure 5. 25 Regression of phase angle between 4PB and 2PB test for AC B 22 H, AC B 22 S, AC T 22 H (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

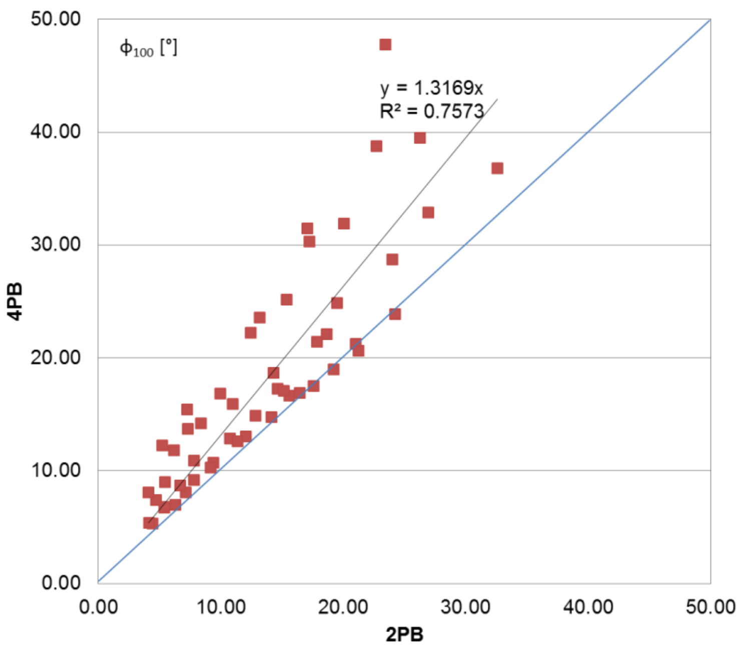


Figure 5. 26 Regression of phase angle between 4PB and 2PB test for AC EME 22, SMA11 and AC MR 8 (10, 15, 20 °C and 3, 10, 25 Hz), equality line shown in blue

Figure 5. 27 Black diagram for SMA 11

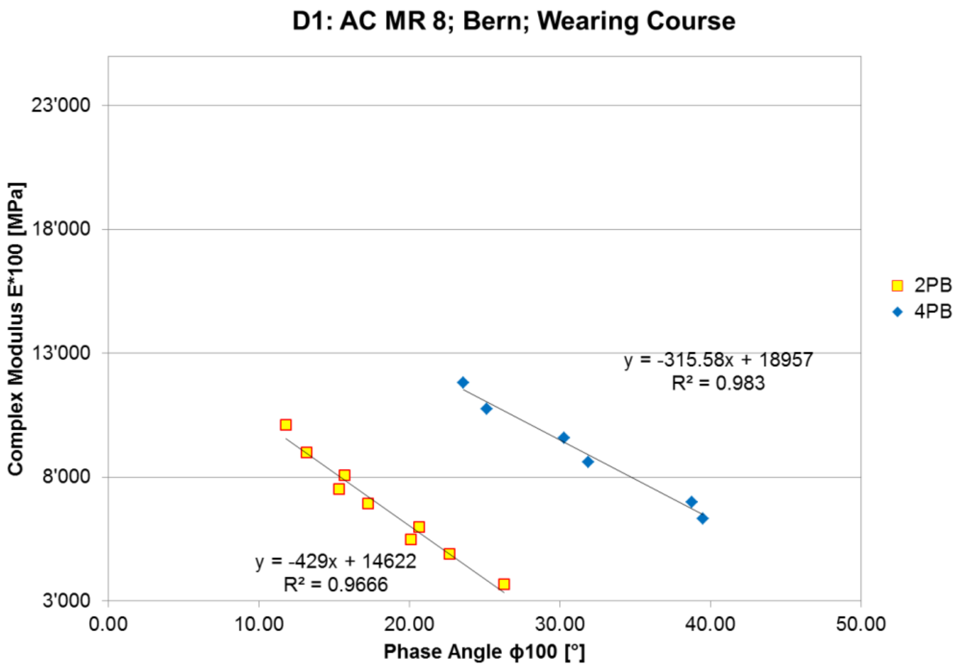


Figure 5. 28 Black diagram for AC MR8, with 4PB results at 25Hz are not shown

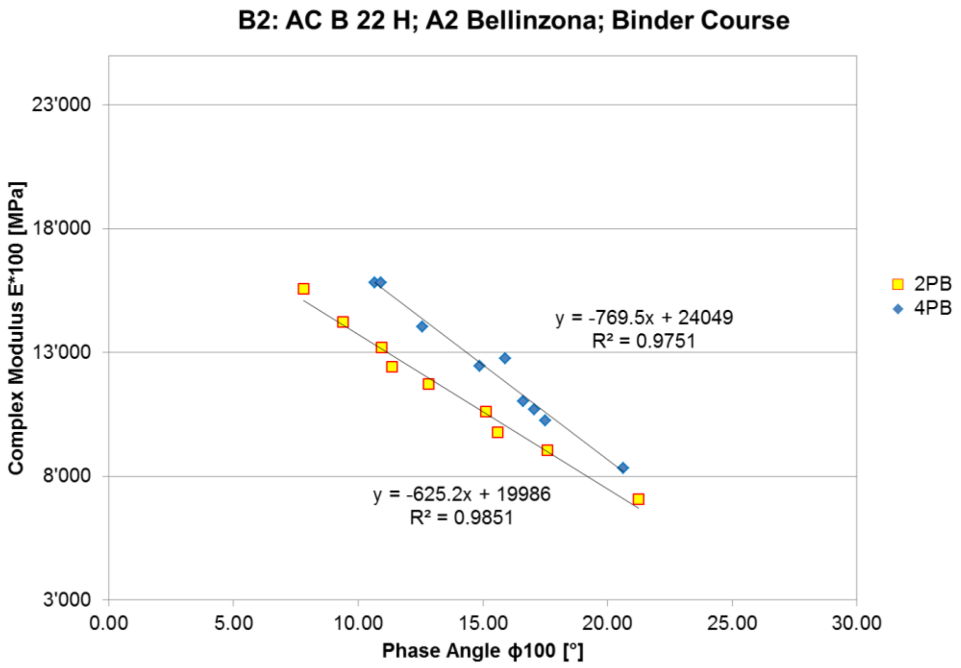


Figure 5. 29 Black diagram for AC B 22 H

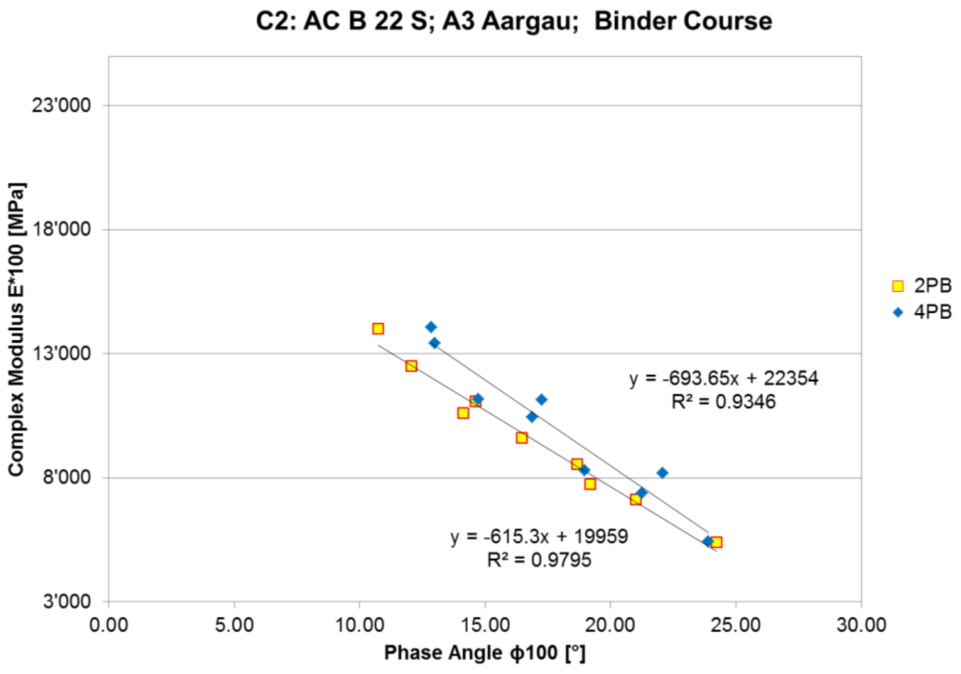


Figure 5. 30 Black diagram for AC B 22 S

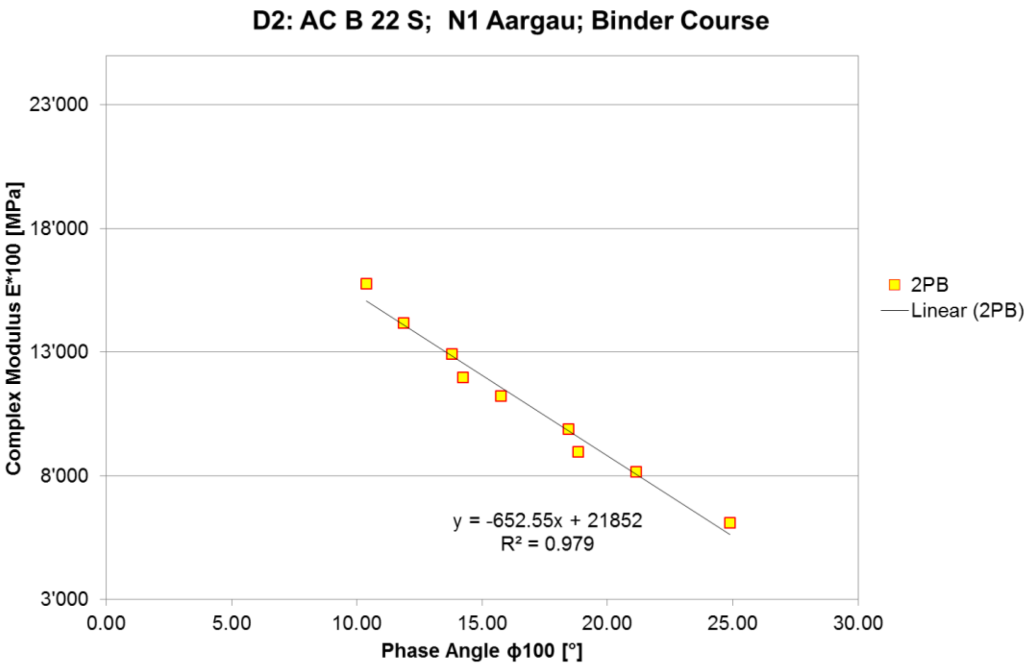


Figure 5. 31 Black diagram for AC B 22S

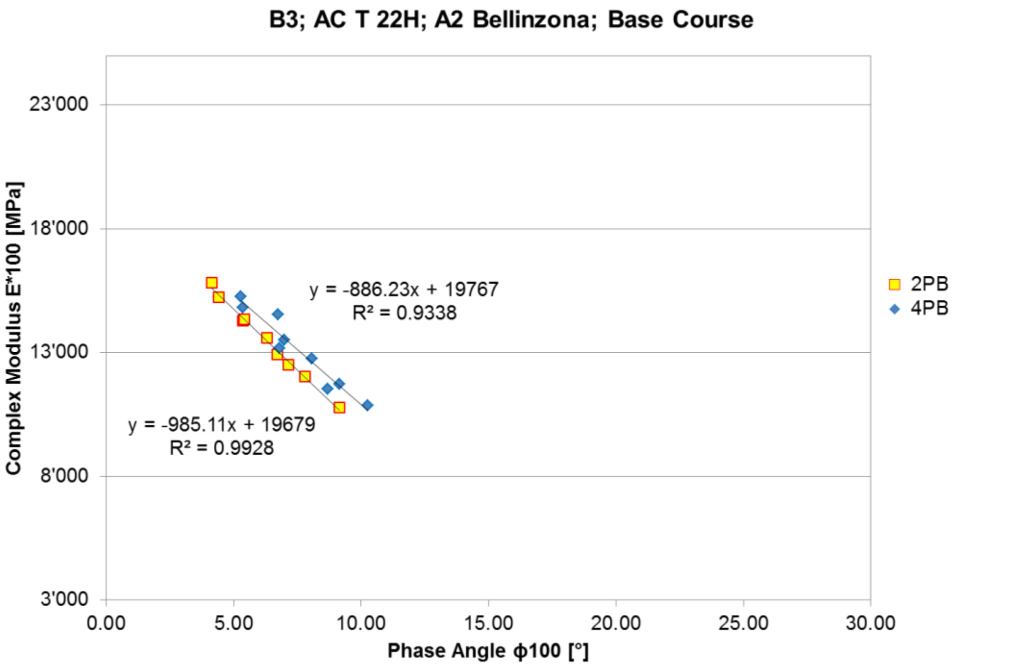


Figure 5. 32 Black diagram for AC T 22

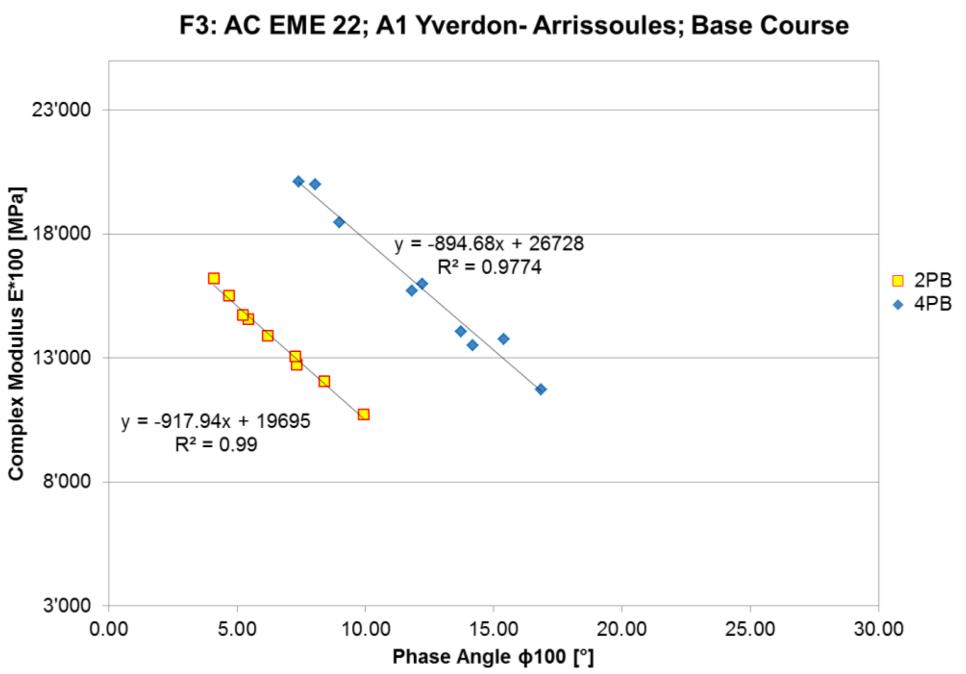


Figure 5. 33 Black diagram for AC EME 22

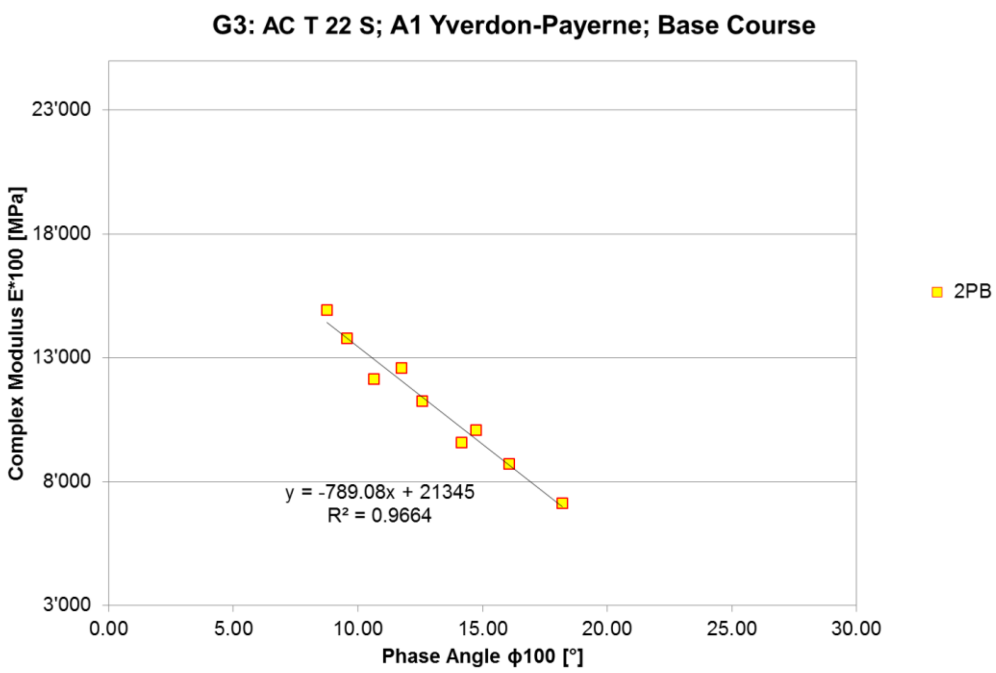


Figure 5. 34 Black diagram for AC T 22 S

Table 5. 1 Pure elastic complex modulus from Black diagrams (N/A: not applicable)

Type	**Layer**	**Mix Designation**	**E^*_{100} @ ϕ=0 [MPa]** 2PB	4PB	% diff
Wearing course	SMA 11	C1	17123	16284	-5
	AC MR 8	D1	14622	18957	30
Binder course	AC B 22 H	B2	19986	24049	20
	AC B 22 S(HMT 22 S)	C2	19959	22354	12
	AC 22 S	D2	21852	N/A	N/A
Base Course	AC T 22 H	B3	19679	19767	0
	AC EME 22 (BBHM 22)	F3	19695	26728	36
	AC T 22 S (HMT 22 S)	G3	21345	N/A	N/A

5.2 Fatigue

During the fatigue tests, the complex modulus continuously reduces and the phase angle continually increases as shown in the example of Figure 5. 35 for AC B 22 H. The test is terminated when the complex modulus reaches 50% of its original value. This is an international standard as well as a European one. As discussed in chapter 1, during a fatigue test, three distinct regions can be identified. In region one the reduction in complex moduls decelerates, in region II the reduction is about linear and in region III the reduction accelerates. In the example shown in Figure 5. 35, the first and second phase of this development can be clearly observed. As this particular test was terminated when the complex modulus reached the 50% value, no third phase can be seen. It can be observed from this data that the specimen's initial modulus defined at 100 cycles was 13973 MPa, and final complex modulus was 6960 MPa. There are some outliers that should be accounted for in the data analysis so that the specimen is not considered already damaged too early. This is accounted for in the 4PB tests by defining failure when 20 consecutive measurements are below the failure criterion. In the 2PB tests, this is accounted for by defining failure when 90 consecutive measurements are below the failure criterion.

The results of the experiments are shown in Figure 5. 36 to Figure 5. 44 keeping in mind the definitions developed in Figure 1. 1. The curves show the relationship between fatigue failure criteria $N_{f/50}$ (or specimen break) and applied strain amplitude ε. These are Wöhler type of curves.

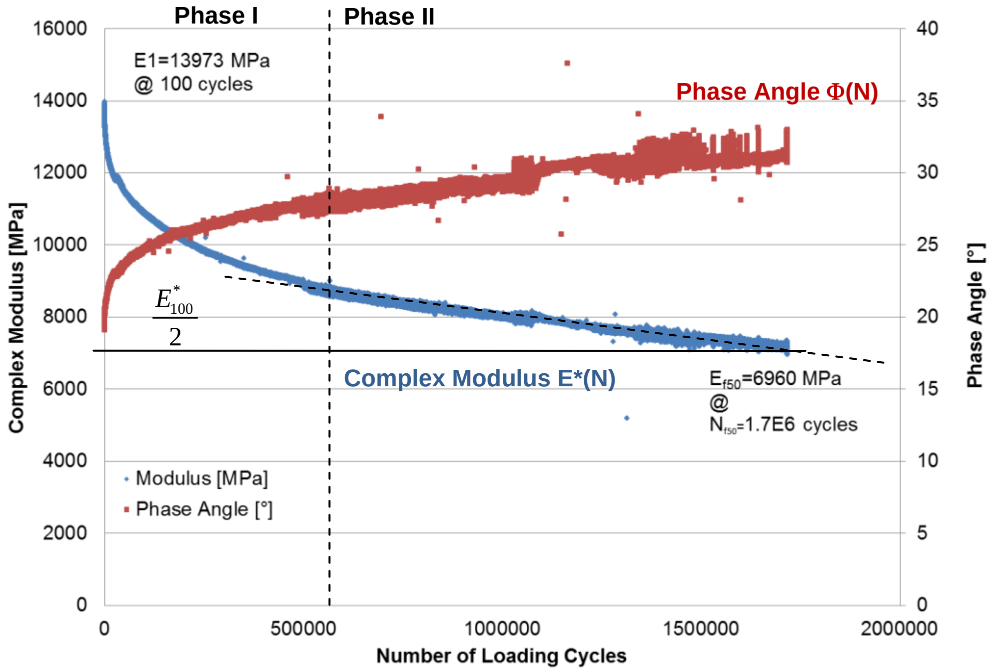


Figure 5. 35 The development of complex modulus and phase angle during a 4PB-PR fatigue tests at 20°C and 25 Hz (sample B21: AC B 22 H)

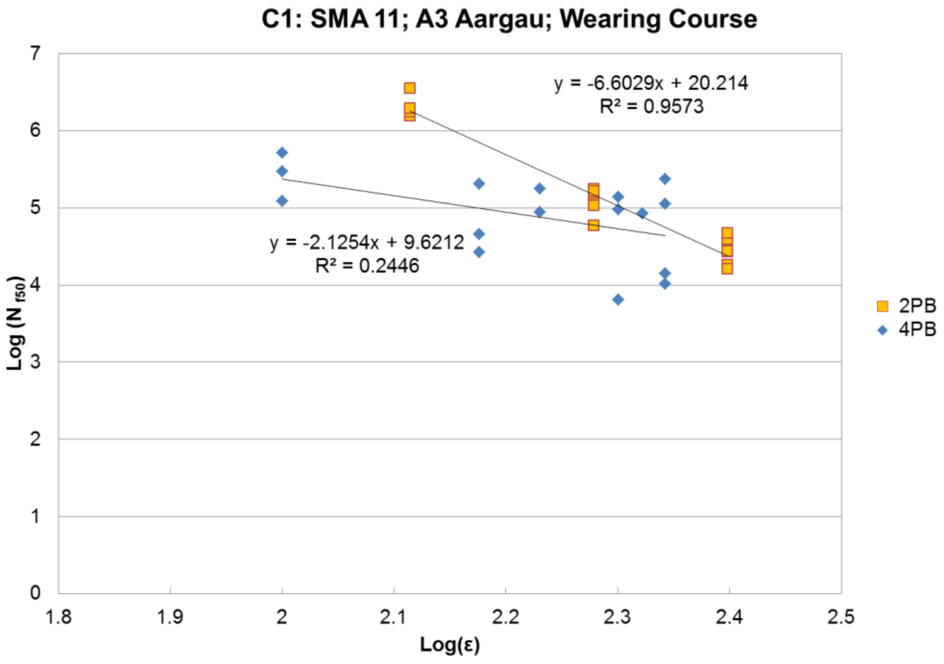


Figure 5. 36 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending at 20°C and 25 Hz and two point bending for SMA11 at 10°C and 25 Hz. All specimen 90° rotated due to the rough surface

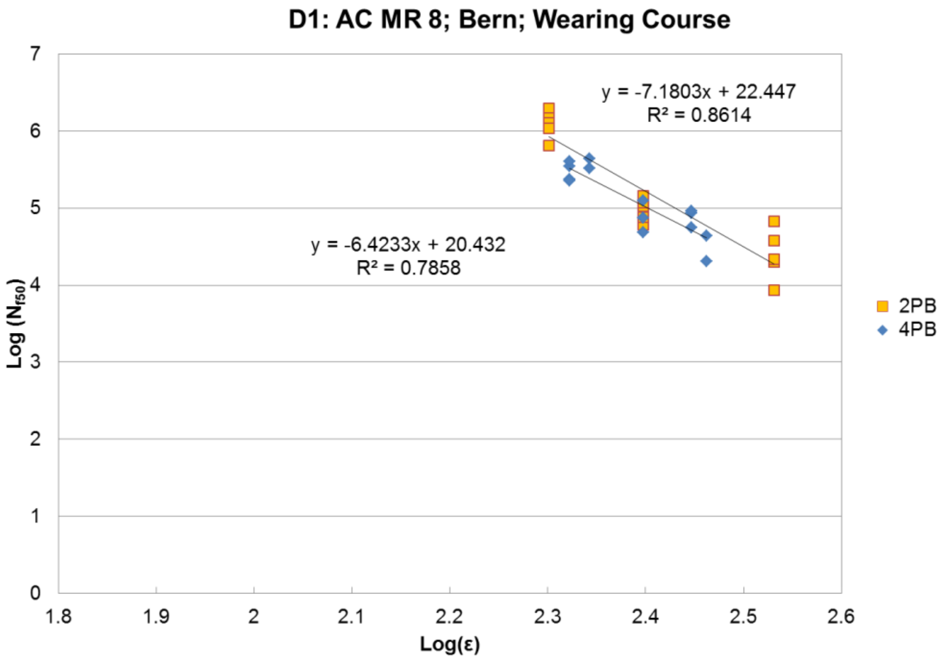


Figure 5. 37 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending at 10°C and 10 Hz, and two point bending at 10°C and 25 Hz for AC MR 8. All specimen 90° rotated due to the rough surface

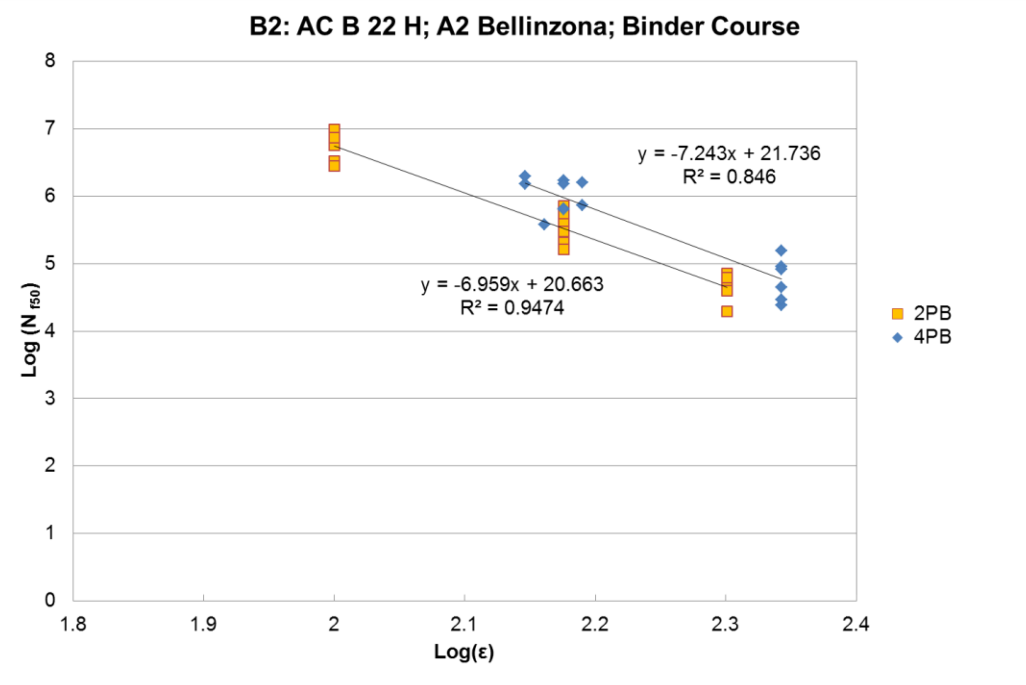


Figure 5. 38 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending 20°C and 25 Hz and two point bending at 10°C and 25 Hz for AC B 22 H

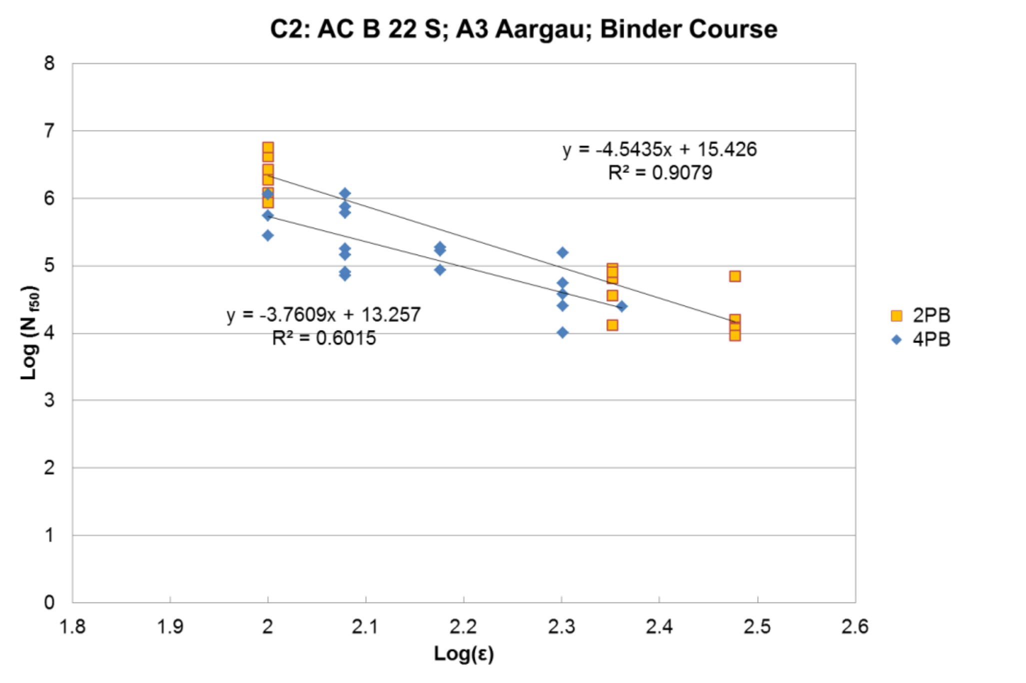


Figure 5. 39 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending 20°C and 25 Hz and two point bending at 10°C and 25 Hz for AC B 22 S

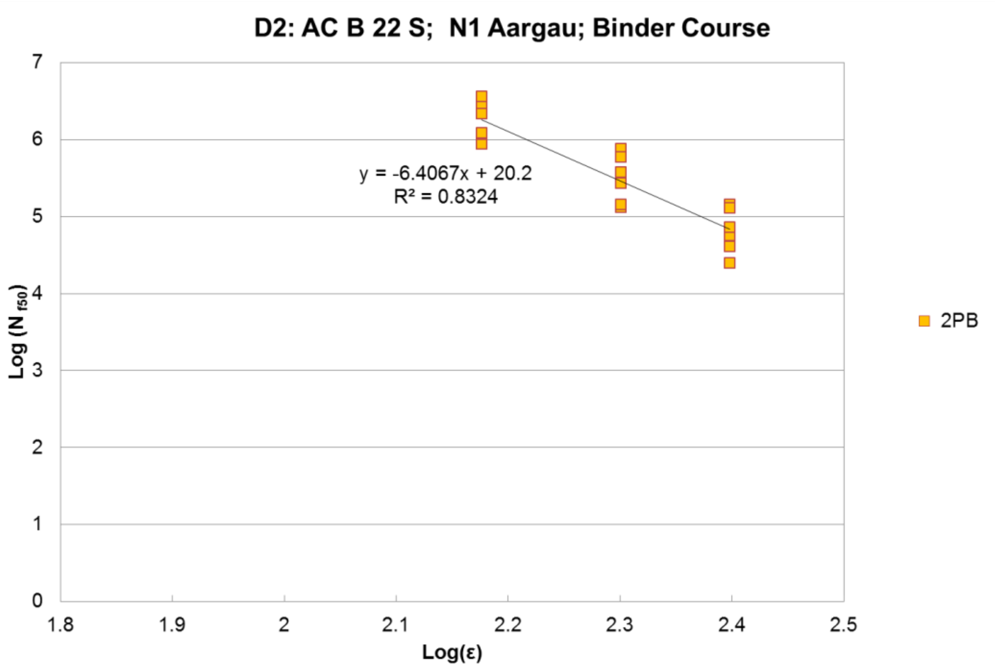


Figure 5. 40 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of two point bending at 10°C and 25 Hz for AC 22 S

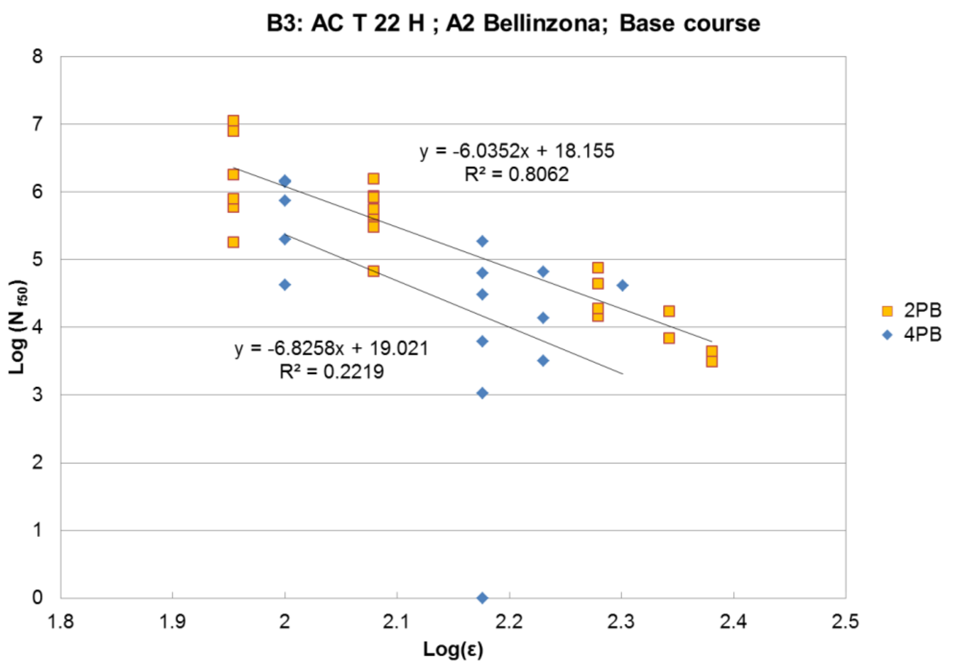


Figure 5. 41 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending at 20°C and 25 Hz and two point bending at 10°C and 25 Hz for AC T 22 H

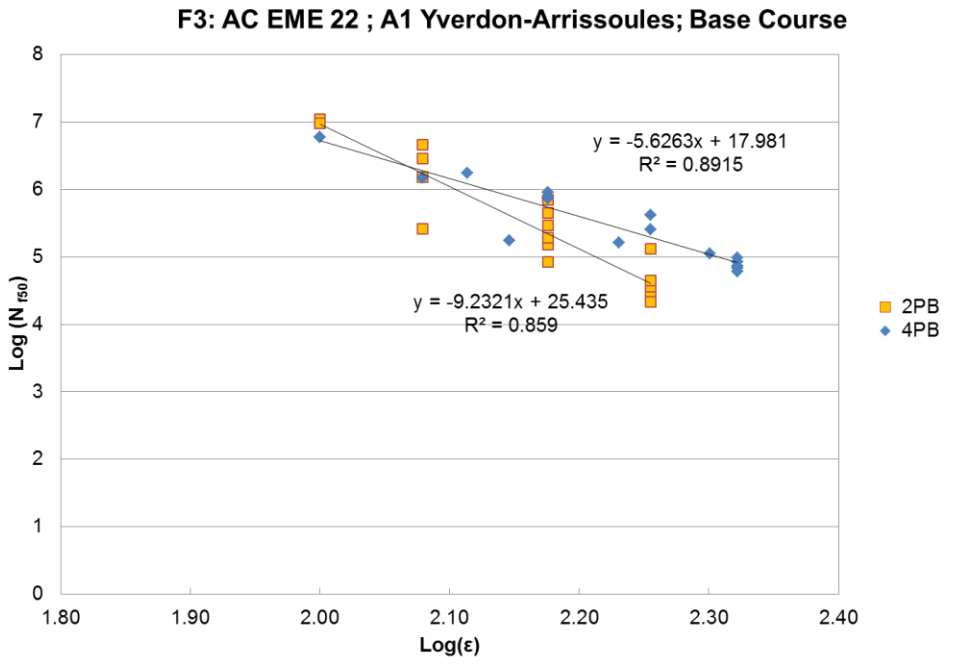


Figure 5. 42 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of four point bending at 20°C and 25 Hz and two point bending at 10°C and 25 Hz for AC EME 22

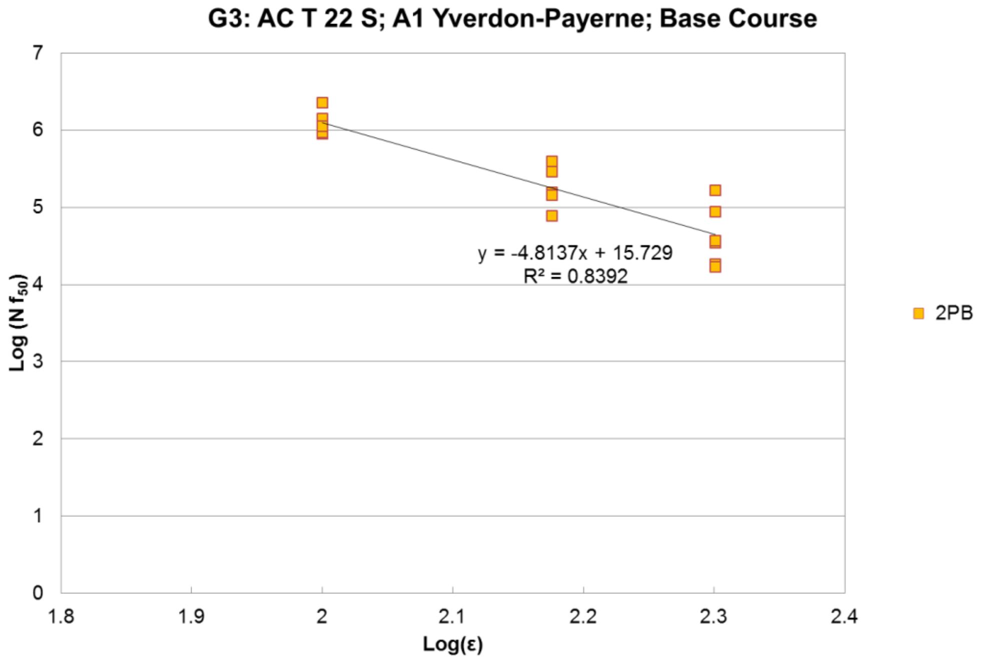


Figure 5. 43 Fatigue diagram showing relationship between fatigue failure criteria $N_{f/50}$ and applied strain amplitude ε of two point bending at 10°C and 25 Hz for AC B 22

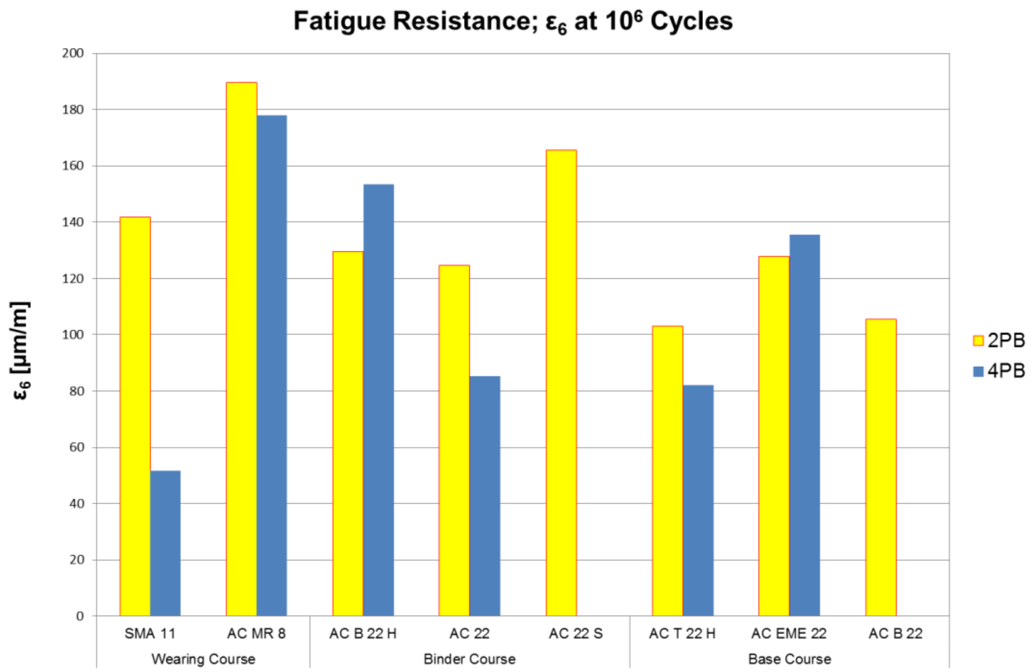


Figure 5. 44 Fatigue Resistance ε_6 at one million cycles for 2PB (at 10°C) and 4PB (at 20°C) tests, with the exception of 4PB AC MR 8 at 10°C

It was shown in chapter 1 that fatigue data obtained using bending tests, where the stress or strain is repeated until the specimen fails, can be expressed using the Wöhler type fatigue line which shall be drawn by making a linear regression between the decimal logarithms of Ni and the decimal logarithms of ε_i having the following shape. Equation (7) is repeated here for the sake of convenience

$$\log(N_f) = a + \left(\frac{1}{b}\right) \bullet Log(\varepsilon) \quad (7)$$

Where, ε is the amplitude of the tensile strain repeatedly applied; a and b are material coefficients; and N_f is the number of load applications to failure. The material coefficient a is the ordinate of the fatigue line and b is the slope. *Table 5. 2* shows the material constants of equation (7) as obtained from the 2PB and 4PB tests on the selected materials. It is clear from these data that the material constants from the two types of experiments are not the same. From the material coefficients a and b, the resistance to fatigue defined by ε_6 can be calculated as shown in equation (7) and shown in *Table 5. 2*.

There is a discrepancy in the standard between the representation of the results as natural logarithm (ln) for 4PB-PR and Logarithm with base 10 (Log) for 2PB-TR. In this study as the goal was to compare results from the two types of tests all fatigue lines have been calculated using Log as in equation (7).

In general there is agreement in some cases between the results shown in Figure 5. 36 to Figure 5. 44. The difference in fatigue resistance obtained through ε6 is shown in Figure 5. ***44*** and Table 5. 2. It can be seen that the ε_6 values vary between 5% and 33%. This difference can be attributed to the different test temperatures.

As mentioned in chapter 4 the fatigue tests were planned to be at 20°C and 25 Hz for 4PB-PR tests and 10°C and 25 Hz for 2PB-TR. The temperature plays a significant role in the modulus values as shown in section 5.1. Thus it can be expected that the fatigue behavior of the two tests would be different. Nevertheless for section D1 the temperature was reduced to 10°C as the cross section of the samples (30 mm x 30 mm) made them too weak for the 4PB test setup. As shown in Figure 5. 37 at 10°C there is good agreement between the 4PB and 2PB results. The largest difference in the fatigue curve can be seen in Figure 5. 36 for SMA11. This difference is also partially due to temperature as well as the small size of the wearing course specimens (40 mm x 40 mm) which made the specimens weak for the 4PB setup, thus producing a large scatter. It is also due to the uncut top surface as discussed in the previous section.

Table 5. 3 shows the initial complex modulus at 100 cycles and standard deviation for both types of tests. The values reported are averages of all 18 samples and for the different strain rates as required by the standard and at different temperatures for 2PB and 4PB as shown in the table. Since the two tests were performed at different temperatures it is expected that the values are not similar. The ranking of the 2PB tests indicates that AC B 22 S is ranked highest and AC MR 8 lowest, whereas with the 4PB tests AC EME 22 is ranked highest and SMA11 lowest. AC MR 8 was not considered in the ranking as it was tested at 10°C resulting in a higher complex modulus.

Figure 5. 44 presents the values of strain ε_6 at one million cycles, an indication of fatigue resistance for all materials tested. In most cases, the ranking obtained is dissimilar. It is important to note that the age and the field performance history of the samples plays a role in defining fatigue life and resistance to fatigue. For example AC MR 8 (D1) was one year in service and has the highest value of ε_6 whereas AC B 22 S (C2) was already 11 years in service with a lower ε_6. The ranking obtained by 4PB indicates AC MR 8 as the most fatigue resistant and SMA11 as the least. This ranking is dissimilar with the 2PB one where also AC MR 8 is ranked highest with AC T 22 being the least fatigue resistant.

The initial complex modulus values obtained from the fatigue tests at 100 cycles and from the complex modulus tests are presented in Table 5. 4 and Table 5. 5. The difference represents the variance for each test method indicating that there is more variance for the 4PB tests as for the 2PB tests. As explained in chapter 4, the 2PB experimental setup is different for fatigue and modulus tests *Table 5. 4* indicates that there is good agreement between the results of the two setups.

Table 5. 2 Material constants and ε_6 obtained from 4PB and 2PB based on equation (7).

2PB-TR at 10°C, 4PB-PR at 20°C both at 25 Hz (= values at 10°C and 10Hz)*

Type	**Layer**	**Mix Desig.**	**2PB a**	**1/b**	**R^2**	**4PB a**	**1/b**	**R^2**	**ε_6 2PB**	**4PB**	**% diff**
Wearing	SMA 11	C1	20.2	-6.6	0.95	9.6	-2.1	0.24	142	52	63
	AC MR 8	D1	22.4	-7.2	0.86	20.4*	-6.4*	0.79*	190	178*	6
Binder	AC B 22 H	B2	20.7	-6.96	0.95	21.74	-7.2	0.85	129	154	-19
	AC B 22 S (HMT 22 S)	C2	15.43	-4.50	0.91	13.26	-3.76	0.6	125	85	32
	AC B 22 S	D2	20.2	-6.40	0.83				165		
Base	AC T 22 H	B3	18.16	-6.04	0.8	19.02	-6.8	0.22	103	82	20
	AC EME 22 (BBHM 22)	F3	25.44	-9.23	0.86	17.98	-5.62	0.89	128	135	-6
	AC T 22 S (HMT 22 S)	G3	15.73	-4.81	0.84				105		

Table 5. 3 Initial complex modulus at 100 cycles, average of 18 samples; (§) values at 10°C and 10Hz

Type pavement	**Layer**	**Mix Des.**	**Initial Complex Modulus 2PB**		**4PB**	
Condition			T[°C] 10	f[Hz] 25	T[°C] 20	f[Hz] 25
			E_{100}* [MPa]	Std Dev.	E_{100}* [MPa]	Std Dev.
Wearing	SMA11	C1	12031	374	6587	1985
course	AC MR 8	D1	9432	426	12997 (§)	3238 (§)
Binder	AC B 22 H	B2	16553	915	8580	806
course	AC B 22 S (HMT 22 S)	C2	13712	767	5322	2801
	AC B 22 S	D2	16096	665	N/A	N/A
Base	AC T 22 H	B3			7732	4568
course	AC EME 22 (BBHM 22)	F3	13937	2661	12770	4864
	AC T 22 S (HMT 22 S)	G3	14540	2661	N/A	N/A

Table 5. 4 Initial complex modulus at 100 cycles and 10°C/25Hz (fatigue test vs complex modulus test) – 2PB-TR

Type	**Layer**	**Mix Designation**	**Complex Modulus E^*_{100} [MPa] Fatigue test**	**Complex modulus test**	**% diff**
Wearing	SMA 11	C1	12031	12575	-4.3
course	AC MR 8	D1	9432	10103	-6.6
Binder	AC B 22 H	B2	16553	15566	6.3
course	AC B 22 S (HMT 22 S)	C2	13712	14007	-2.1
	AC B 22 S	D2	16096	15782	2.0
Base	AC T 22 H	B3	12176**	15825	-23.1
		B3.1	15805***	15825	-0.1
Course	AC EME 22 (BBHM 22)	F3	13937	16204	14.0
	AC T 22 S (HMT 22 S)	G3	14540	14938	-2.7

*** Average value of 23 specimens (9 specimens with very significant structural defects)*
**** Average value of 14 healthy specimens*

Table 5. 5 Initial complex modulus at 100 cycles and 20°C/25Hz (fatigue test vs. complex modulus test)– 4PB-PR

Type	**Layer**	**Mix**	**Complex Modulus E^*_{100} [MPa]**		
		Desig.	**Fatigue test**	**Complex Modulus test**	**% diff**
Wearing course	SMA 11	C1	6479	7250	-12
	AC MR 8*	D1	13142	11797	10
Binder course	AC B 22 H	B2	9597	10696	-11
	AC B 22 S (HMT 22 S)	C2	6653	8186	-23
	AC B 22 S	D2	N/A	N/A	N/A
Base Course	AC T 22 H	B3	9021	11500	-27
	AC EME 22 (BBHM 22)	F3	12770	13800	-8
	AC T 22 S (HMT 22 S)	G3	N/A	N/A	N/A

**Tests at 10°C/25Hz*

6 Executive Summary of Results and Conclusions

Project goals

The goal of this project was to perform 2PB and 4PB tests in accordance to the European standards investigating asphalt samples from trafficked road pavements. The procedure defined in the European standards is used to rank fresh bituminous mixtures on the basis of complex stiffness modulus and fatigue performance, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for bituminous mixtures. However, since performance oriented requirements are supposed to improve the expected life of pavements, this project was focused on performance oriented fatigue properties, conducting the tests on samples from real roads with known performance and not on fresh laboratory compacted samples as normally required by the European standards. Hence, the fatigue life characteristics reported in this study were expected to be lower than those for freshly compacted samples used for type testing. Given these project goals and scope, the results of this research can be summarized as described in the following paragraphs.

National annex

There is a discrepancy between the national annex defining requirements for complex modulus [SN 640 431-1b-NA] and the national annex for type testing [SN 640 431-20b-NA]. The type testing NA requires the complex modulus to be performed using 2PB on trapezoidal specimen whereas the complex modulus NA does not specify any specific test. This discrepancy should be corrected.

The standard limits the tests to specimen with maximum aggregate size up to 20 mm. This needs to be corrected as some European countries such as Switzerland have different sieve sizes that allow 22 mm aggregates. The tests performed in this project included samples with maximum aggregate size of D=22 mm.

Materials

The sections chosen were sawn from slabs taken from trafficked road pavements. These slabs were from 1 to 14 years old when extracted. Using field slabs eliminates the effect of various laboratory compaction methods and was therefore considered suitable for this comparative performance oriented study.

Test parameters

2PB tests were performed on trapezoidal samples and 4PB on prismatic ones. 4PB samples were tested with the exception of one material, with the road surface upwards whereas due to sample size, trapezoidal specimens were sometimes tested 90° flipped.

A total of 252 experiments were performed on eight types of mixes from Swiss motorways.

Complex modulus experiments to determine initial complex stiffness modulus after 100 cycles were performed at 10°C, 15°C and 20°C each at 3, 10 and 25 Hz frequency.

Fatigue experiments were performed at 10°C and 25 Hz for 2PB tests and 20°C and 25Hz for 4PB tests, with the exception of AC MR 8 which was tested at 10°C and 10 Hz. This alteration to test condition was made as the samples were very slender and “soft” at 20°C.

Summary of results

The two surface courses with 40 mm and 30 mm depth were too thin to provide adequate specimens for these experiments; nevertheless, they were tested and results presented. However, it should be noted that surface courses of Swiss motorways are not subjected to fatigue failure in bending mode and from a practical point of view there is no need to evaluate their fatigue performance. In general, we do not recommend determining fatigue bending properties of pure surface courses for pavements with stiff base and subbase.

The results show more scatter in the data of 4PB tests in comparison to 2PB tests. Using the regression comparing complex modulus values of 4PB and 2PB (Figure 5. 21) it was shown that 4PB values were about 8% higher than 2PB tests. Specific values are listed in Table 6. 2.

A linear regression between 2PB and 4PB tests with correlation coefficient R^2 of 0.84 for complex modulus and 0.76 for phase angle was determined.

The complex modulus results of 4PB tests at 3 Hz and 10 Hz were in agreement with 2PB however at 25 Hz the 4PB results were below expected values in some cases.

The pure elastic complex modulus obtained from black diagrams for the 2PB and 4PB tests were not equal in most cases.

The current requirements in the Swiss standards are listed in Table 6. 1. Based on the experiments performed in this research project values were obtained for complex modulus (E^*_{100}) and resistance to fatigue (ε6) as summarized in Table 6. 2. As shown in this table the values obtained for AC EME 22 fulfill the requirements in Table 6. 1. It is important to note that these tests were performed on aged specimen from the road and actual complex modulus and resistance to fatigue values for production of new materials can be different from these.

The tests presented in this report are on samples from slabs taken from the road and not freshly laboratory compacted samples. Therefore, as for standardization, these findings should be considered keeping in mind that the modulus reported here is most probably higher and fatigue life lower than for freshly field compacted samples of the same materials. Furthermore, field compaction results in different samples compared to lab compacted samples which are used for type testing.

It is recommended that a new project is formulated with the goal of providing minimum values for type testing of asphalt concrete materials. To this end, a series of tests should be designed to investigate the complex modulus and fatigue resistance of laboratory prepared samples produced from current mixes in Swiss plants. These tests should be performed with different specimens providing a means to rank road materials with respect to their long term performance.

Table 6. 1 Minimum values from current Swiss Standards using 2PB-TR specimen

	Type of mix	Complex Stiffness Modulus E^*_{100} at 15°C, 10 Hz [MPa]	Fatigue resistance, ε_6, at 10°C, 25Hz [µm/m]
Existing Swiss Standard [SN 640 431-1b-NA]	AC EME C1	≥ 11000	≥ 100
	AC EME C2	≥ 14000	≥ 130

Table 6. 2 Average values obtained from 2PB-TR and 4PB-PR experiments (= values at 10°C and 10Hz) refer Figure 5. 19 and Figure 5. 44*

	Type of mix	E^*_{100} at 15°C, 10 Hz[1] [MPa]	E^*_{100} at 15°C, 10 Hz[2] [MPa]	ε_6, at 10°C, 25Hz[1] [µm/m]	ε_6, at 20°C, 25Hz[2] [µm/m]
Wearing	SMA11	8000	10000	140	50
	AC MR 8	6000	9000	180	180*
Binder	AC B 22 S	9000	10000	130	150
Base	AC T 22 H	13000	13000	100	80
	AC EME 22	14000	15000	130	130

[1] *using 2PB-TR tests*
[2] *using 4PB-PR tests*

7 Recommendations for Performing Stiffness and Fatigue Tests

The concept of fatigue life is based on the idea that most materials undergo a gradual deterioration under repeated loads that are much smaller than the ultimate strength of the material. Therefore, knowledge of fatigue behavior of asphalt concrete materials is imperative for material evaluation.

In order to perform tests in accordance to the European standards for stiffness and fatigue in accordance to EN 12697-24 and 26 the following is recommended based on the literature and experiments performed in this project:

1. Tests can be performed on laboratory prepared samples or cut from field slabs. Experience has shown that the repeatability is better with laboratory prepared samples for example using the French wheel tracking compactor.
2. The standard limits the tests for specimen with maximum aggregate size of up to 20 mm. This needs to be corrected as some European countries such as Switzerland have different sieve sizes that allow 22 mm aggregates. The tests performed in this project included samples with maximum aggregate size, D of 22 mm.
3. In the case of prismatic samples, the beam should be sawed on all sides. The distance of the beam to the border of the slab should be at least 20 mm. If the thickness of the road layer is too small to meet the requirement with respect to the ratio between height H and the maximum grain size D (H>3*D), the beams shall be rotated over an angle of 90°. However, this has to be clearly reported. The experience in this project confirms that it is important to have a height of ca. 50mm
4. The testing equipment should be checked periodically using at least one reference specimen with known modulus such as an aluminum specimen with modulus of around 70 GPa. The tests should be done at least at 6 frequencies and 2 deflection levels. The back-calculated stiffness modulus and phase lag should be within 2% and 1.0° from known values.
5. For complex (stiffness) modulus measurements, for most bituminous mixtures strains should be kept lower than 50 microstrain (= 50×10^{-6} m/m) to remain in the linear viscoelastic range.
6. Tests are performed in constant strain amplitude mode.
7. The specimen shall be placed in the climatic chamber for at least 4 h before testing.
8. Initial complex (stiffness) modulus is defined as complex modulus at the 100th cycle.
9. In addition to the initial complex modulus also the initial phase angle should be determined
10. Fatigue failure is defined when the complex modulus reaches 50% of the initial value or when the sample fails whichever occurs sooner.
11. During fatigue tests also the phase angle should be recorded.
12. Testing time: depending on the strain rate, it can take days or weeks to obtain enough data for a particular mixture.
13. Choice of strain rate for 2PB-TR: The strain rate shall be chosen such that at least one third of the element tests provide results with $N \leq 10^6$ and at least one third of the element tests provide results with $N \geq 10^6$. *Table 6. 1* can be used as an indication of strain rate to reach 10^6 cycles for various HMA mixtures.
14. Choice of strain rate for 4PB-PR: The strain rate shall be chosen such that fatigue life is within the range 10^4 and 2×10^6 cycles. *Table 6. 1* can be used as an indication of strain rate to reach 10^6 cycles for various hot mix asphalt mixtures.
15. The following factors can affect the results:

a. Bulk density of the sample; The results obtained in this project indicate that there is no direct relationship between bulk density and fatigue life as other factors such as inhomogeneity of samples play a greater role.

b. Maximum aggregate size; higher maximum aggregate size results in a more heterogeneous structure and as a result more scatter in data.

c. Micro structure of the sample under the load or support location. When a damaged aggregate is directly under the support, the sample may fail at this location earlier.

d. Temperature

e. Compaction and specimen production

8 Recommendations for Standardization According to EN 12697-24 and 26

Surface courses of Swiss motorways are not subjected to fatigue failure in bending mode and from a practical point of view there is no need to evaluate their fatigue performance. In general, we do not recommend determining fatigue bending properties of pure surface courses for pavements with stiff base and subbase.

Laboratory compacted samples or field compacted fresh samples should be used for type testing. However, compaction and specimen production should be standardized and validated in round robin tests, since these aspects are expected to have significant influence on the scatter and reliability of the results.

The tests presented in this report are on samples from slabs taken from the road and not fresh laboratory compacted samples. Therefore, as for standardization, these findings should be considered keeping in mind that the complex modulus reported here (*Table 6. 2*) is most probably higher and fatigue life lower than for freshly compacted samples of the same materials.

The experiments performed in this research project using 2PB and 4PB tests on AC EME 22 fulfill the current requirements in the Swiss standards for complex modulus and fatigue that are listed in Table 6. 1.

Both, four point bending tests (4PB) on prismatic samples and two point bending tests (2PB) on trapezoidal samples can be used to determine complex modulus of asphalt samples as this research project has shown that the results for all types of pavements are in agreement with each other.

Regarding resistance to fatigue failure the results of the two tests cannot be directly compared as they were performed at different temperatures resulting in different ranking as the performance of the materials is highly temperature dependent. This is demonstrated in Figure 8. 1. However, since fatigue performance and ranking can change depending on the testing temperature it is recommended to perform fatigue tests at two different temperatures (i.e. at 10°C and 20°C) in case of pavement structures where fatigue may be of major concern.

It is recommended that a new project is formulated with a series of tests that are designed to investigate the complex modulus and fatigue resistance of laboratory prepared samples produced from current mixes in Swiss plants. The project should include 2PB, 4PB and IT-CY (Indirect tensile test). The latter has shown promising results in recent round robin tests. Furthermore a selected range of temperatures and frequencies should be defined in order to provide enough data for ranking of pavements.

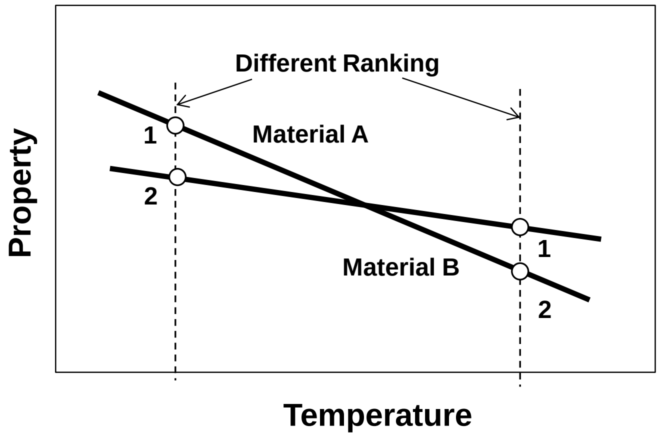


Figure 8. 1 The properties of asphalt concrete are highly temperature related

Acknowledgements

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For the LAVOC, the formulas were analyzed and the specimen were cut and prepared by Jean-Claude Reymond and Jean-Wilfried Fils-Aimé.

Abbreviations and Definitions

Symbol	Explanation
2PB-TR	two point bending tests on trapezoidal specimens
4PB-PR	four point bending tests on prismatic specimens
ASTRA	Bundesamt für Strassen, Federal Roads Office (FEDRO)
CAST	Coaxial shear test
DATEC	Dipartimento federale dell'ambiente, dei trasporti, dell'energia e delle comunicazioni
DETEC	Département fédéral de l'environnement, des transports, de l'énergie et de la communication
E*	Complex modulus (or complex stiffness modulus) [MPa]
E^*_{100}	Complex Modulus of mix defined as Modulus at the 100th loading cycle
E_1 E_2	The real part and the imaginary part of the complex modulus
EMPA	Swiss federal laboratory for materials science and technology
EN	European standard
EPFL	Ecole polytechnique fédérale de Lausanne
ETH	Eidgenössische technische Hochschule, Swiss federal institute of technology
f	Frequency [Hz]
F	Force [N]
LAVOC	Laboratoire des voies de circulation
LVDT	Inductive deformation sensor (linear variable differential transformer)
M and m	*Mass of specimen and mass of moving parts respectively [g]*
MEPDG	Mechanistic empirical design guide
M_R	Richness modulus
N	Number of loading cycles
N_{f50}	Number of loading cycles to reach 50% of initial stiffness E^*_{100}
R^2	Statistical correlation coefficient
RILEM	International union of laboratories and experts in construction materials, systems and structures
SHRP	Strategic Highway Research Program

Symbol	Explanation
SN	Swiss standard
T	Temperature
UVEK	Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation
VSS	Schweizerischen Verbandes der Strassen- und Verkehrsfachleute/ Swiss association of road transportation experts
z	Displacement [mm]
γ , μ	Form factor, mass factor
ε	Strain [µm/m]
ε_6	Strain to reach 10^6 loading cycles [µm/m]
ε_i	Chosen strain (usually i=3) [µm/m]
ϕ	Phase angle [°]
ω	The angular frequency=$2\pi f$

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NA]	phaltmischgut- Mischgutanforderungen-teil 1: Asphaltbeton; nationaler Anhang
[SN 640 431-20b-NA]	Asphaltmischgut Mischgutanforderungen teil 20: Erstprüfung Nationaler Anhang zu EN 13108-20:2006/AC:2008

Projektabschluss

Schweizerische Eidgenossenschaft
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FORSCHUNG IM STRASSENWESEN DES UVEK

Formular Nr. 3: Projektabschluss

erstellt / geändert am: 21.06.2013 / Bk 27.06.2013

Grunddaten

Projekt-Nr.: VSS 2006/503

Projekttitel: Performance orientierte Mischgutanforderungen

Enddatum: Juli 2013

Texte

Zusammenfassung der Projektresultate:

The European standards specify methods for characterizing the stiffness and fatigue behavior of bituminous mixtures by alternative tests, including bending tests. The tests are performed on compacted bituminous materials under sinusoidal loading. The procedures are used to rank bituminous mixtures on the basis of stiffness, as a guide to relative performance in the pavement, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for bituminous mixtures. This project has developed recommendations for various asphalt concrete mixes used in Switzerland using the 2 point bending test on trapezoidal specimen (2PB-TR) and four point bending test on prismatic specimen (4PB-PR).
Using performance oriented requirements the expected life of pavements can be improved. Currently in Switzerland, performance oriented requirements exits for AC-EME, [SN 640 431-1b-NA].
The goal of this project was to perform 2PB and 4PB tests on asphalt samples in accordance to the European standards in order to determine if both tests could be used alternatively or if there is a relationship between the results. Tests were done on slabs from test sections that were sawn from trafficked road pavements. These slabs were from 1 to 14 years old when extracted. Field slabs were used in order to eliminate the effect of various laboratory compaction methods.
A total of 252 experiments were performed on eight types of mixes from Swiss motorways. Stiffness tests to determine complex modulus were performed at 10°C, 15°C and 20°C each at 3, 10 and 25 Hz frequency. Fatigue tests were performed at 10°C and 25 Hz for 2PB-TR tests and 20°C and 25Hz for 4PB-PR tests. Both in deformation control mode as prescribed by the standards.
The results presented indicate that complex modulus and phase angle values of 4PB-PR are consistently higher than 2PB-TR tests, although the difference for all AC 22 layers was minimal.

Using all complex modulus and phase angle data determined at 10, 15 and 20 °C and at 3, 10 and 25 Hz frequencies, a linear regression between 2PB-TR and 4PB-PR with correlation coefficient R2=0.84 for complex modulus and R2=0.76 for phase angle was obtained.
The pure elastic modulus, i.e. modulus at low temperature or zero phase angle, obtained from Black diagrams for the 2PB-TR and 4PB-PR tests are not equal in most cases.

In addition, the results in this project indicate that although there is more scatter in the 4PB results, for the tests that are performed according to the standards, for complex modulus the same ranking was obtained. However, keeping in mind that the tests were performed at different temperatures, fatigue resistance values obtained using 4PB and 2PB were not similar in each case studied. Based on the experiments performed in this research project values were reported for complex modulus and resistance to fatigue as basis for further consideration for standardization. However it should be noted that these values were obtained using materials after being in service for several years and not for new materials.
The pavement specimens tested in this project fulfill the requirements in the national annex for AC EME 22. However, for the purpose of standardization it is recommended that a new project is formulated to define the required values for complex modulus and resistance to fatigue for lab specimens produced from current Swiss pavement mixtures.

Zielerreichung:

2PB-TR and 4PB-PR tests have been performed in accordance to European standards on eight types of pavement and results were compared. The tests presented in this report are on samples from slabs taken from the road and not freshly laboratory compacted samples. Therefore, as for standardization, these findings should be considered keeping in mind that the modulus reported here is most probably higher and fatigue life lower than for freshly field compacted samples of the same materials. Furthermore, field compaction results in different samples compared to lab compacted samples which are used for type testing.

Folgerungen und Empfehlungen:

Based on the experiments performed in this research project values were obtained for complex modulus and resistance to fatigue.
Recommendations have been made for performing complex modulus and fatigue tests in accordance to european standards.
It is further recommended that a new project is formulated with a series of tests that are designed to investigate the modulus and fatigue resistance of laboratory prepared samples as required for the type testing tests produced from current mixes from Swiss plants.

Publikationen:

Schlussbericht 2013
Scientific paper planned 2013

Der Projektleiter/die Projektleiterin:

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Amt, Firma, Institut: Empa

Unterschrift des Projektleiters/der Projektleiterin:

Lily Poulikakos Lily Poulikakos

Forschung im Strassenwesen des UVEK: Formular 3 **Seite 2 / 3**

Schweizerische Eidgenossenschaft
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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK

Formular Nr. 3: Projektabschluss

Beurteilung der Begleitkommission:

Beurteilung:

Die Begleitkommission ist mit dem gegenüber dem Forschungsgesuch reduzierten Prüfumfang einverstanden. Alle Prüfungen erfolgten an Belagsausschnitten. Ein Teil der für diesen Forschungsauftrag entnommenen Ausschnitte konnte wegen vorhandener Beeinträchtigungen nicht geprüft werden und auf die Prüfung von zwei neu aufbereiteten Mischgut-Sorten wurde verzichtet. Die vorgesehene Anzahl von zwei Mischgut-Sorten ist viel zu gering, um Aussagen im Hinblick auf die Anwendung der Versuche für Erstprüfungen machen zu können.
Die Prüfungen an Ausschnitten haben sich bewährt, um die Beständigkeit gegen Ermüdung nach EN 12697-24 und die Steifigkeit nach EN 12697-26 anhand der zwei Prüfverfahren Zweipunkt-Biegung 2PB-TR (Trapez) und Vierpunkt-Biegung 4PB-PR (Prisma) zu vergleichen.
Die Ergebnisse der Steifigkeit nach EN 12697-26 zeigen, dass die Werte von komplexem Modul und Phasenwinkel bei 4PB-PR mehrheitlich höher sind als bei 2PB-TR. Die Ergebnisse der 4PB-PR streuen stärker als diejenigen der 2PB-TR, rangieren aber praktisch gleich. Die Werte für den komplexen Modul bei der 4PB-PR sind um etwa 8% höher.
Für die Ermüdung nach EN 12697-24 ist die Rangierung nicht in allen Fällen gleich. Diese wurden den Normen entsprechend bei verschiedenen Prüftemperaturen ermittelt, bei 10°C und 25 Hz für 2PB-TR, bei 20°C und 25 Hz für 4PB-PR.

Umsetzung:

Das Forschungsvorhaben konnte nicht vollständig umgesetzt werden. Da alle Prüfungen an Ausschnitten aus unterschiedlich alten Belägen und mit unterschiedlichen Verkehrsbeanspruchungen stammen, können die erarbeiteten Werte für die Steifigkeit nach EN 12697-26 und die Ermüdung nach EN 12697-24 mit 2PB an Trapez- und mit 4PB an prismatischen Prüfkörpern nur als Anhaltspunkte für Prüfungen an Neumischgut angesehen werden. Für präzisere Aussagen wären weitere Untersuchungen an neu aufbereiteten Schweizer Mischgutsorten und an im Labor verdichteten Prüfkörpern erforderlich gewesen.

weitergehender Forschungsbedarf:

Der weitere Forschungsbedarf ist im Kapitel 8 "Recommendations for Standardization according to EN 12697-24 and -26" ausgeführt. Weitere Forschung ist notwendig, wenn performance orientierte Mischgutanforderungen im Schweizerischen Normenwerk an die Ermüdung nach EN 12697-24 und an die Steifigkeit nach EN 12697-26 umgesetzt werden sollen.

Einfluss auf Normenwerk:

Die vorliegende Forschungsarbeit hat keinen Einfluss auf das Normenwerk. Das Ziel performance orientierte Mischgutanforderungen an die Ermüdung nach EN 12697-24 und an die Steifigkeit nach EN 12697-26 vorzuschlagen, konnte nicht erreicht werden. Es sind aber keine Widersprüche zu den aktuell normierten Anforderungen festgestellt worden.

Der Präsident/die Präsidentin der Begleitkommission:

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Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

M. Seeberger

Verzeichnis der Berichte der Forschung im Strassenwesen

Bericht-Nr.	Projekt Nr.	Titel	Datum
1356	SVI 2007/014	Kooperation an Bahnhöfen und Haltestellen *Coopération dans les gares et arrêts* *Coopération at railway stations and stops*	2011
1362	SVI 2004/012	Aktivitätenorientierte Analyse des Neuverkehrs Activity oriented analysis of induced travel demand Analyse orientée aux acitivtés du trafic induit	2012
1361	SVI 2004/043	Innovative Ansätze der Parkraukmbewirtschaftung Approches innovantes de la gestion du stationnement Innovative approaches to parking management	2012
1357	SVI 2007/007	Unaufmerksamkeit und Ablenkung: Was macht der Mensch am Steuer? Driver Inattention and Distraction as Cause of Accident: How do Drivers Behave in Cars? L'inattention et la distraction: comment se comportent les gens au volant?	2012
1360	VSS 2010/203	Akustische Führung im Strassentunnel Acoustical guidance in road tunnels Guidage acoustique dans les tunnels routiers	2012
1365	SVI 2004/014	Neue Erkenntnisse zum Mobilitätsverhalten dank Data Mining? De nouvelles découvertes sur le comportement de mobilité par Data Mining? New findings on the mobility behavior through Data Mining?	2011
1359	SVI 2004/003	Wissens- und technologientransfer im Verkehrsbereich Know-how and technology transfer in the transport sector Transfert de savoir et de technologies dans le domaine des transports	2012
1363	VSS 2007/905	Verkehrsprognosen mit Online -Daten Pronostics de trafic avec des données en temps réel Traffic forecast with real-time data	2011
1367	VSS 2005/801	Grundlagen betreffend Projektierung, Bau und Nachhaltigkeit von Anschlussgleisen Principes de bases concernant la conception, la construction et la durabilité de voies de raccordement Basic Principles on the Design, Construction and Sustainability of Sidings	2011
1370	VSS 2008/404	Dauerhaftigkeit von Betongranulat aus Betongranulat	2011
1373	VSS 2008/204	Vereinheitlichung der Tunnelbeleuchtung	2012
1369	VSS 2003/204	Rétention et traitement des eaux de chaussée	2012
648	AGB 2005/023 + AGB 2006/003	Validierung der AAR-Prüfungen für Neubau und Instandsetzung	2011

1371	ASTRA 2008/017	Potenzial von Fahrgemeinschaften *Potentiel du covoiturage* *Potential of Car Pooling*	2011
1374	FGU 2004/003	Entwicklung eines zerstörungsfreien Prüfverfahrens für Schwiessnähte von KDB *Dévelopment d'une méthode d'éssais non-déstructif pour des soudures de membranes polymères d'étanchéité* *Development of a nondestructive test method for welded seams of polymeric sealing membranes*	2012
1375	VSS 2008/304	Dynamische Signalisierungen auf Hauptverkehrsstrassen *Signalisations dynamiques sur des routes principales* *Dynamic signalling at primary distributors*	2012
1376	ASTRA 2011/008_004	Erfahrungen im Schweizer Betonbrückenbau *Expériences dans la construction de ponts en Suisse* *Experiences in Swiss Bridge Construction*	2012
1379	VSS 2010/206_OBF	Harmonisierung der Abläufe und Benutzeroberflächen bei Tunnel-Prozessleitsystemen *Harmonisation of procedures and user interface in Tunnel-Process Control Systems* *Harmonisation des processus et des interfaces utilisateurs dans les systèmes de supervision de tunnels*	2012
1380	ASTRA 2007/009	Wirkungsweise und Potential von kombinierter Mobilität *Mode of action and potential of combined mobility* *Mode d'action et le potentiel de la mobilité combinée*	2012
1381	SVI 2004/055	Nutzen von Reisezeiteinsparungen im Personenverkehr *Bénéfices liés à une réduction des temps de parcours du trafic voyageur* *Benefits of travel time savings in passenger traffic*	2012
1383	FGU 2008/005	Einfluss der Grundwasserströmung auf das Quellverhalten des Gipskeupers im Chienbergtunnel *Influence de l'écoulement souterrain sur le gonflement du Keuper gypseux dans le Tunnel du Chienberg* *Influence of groundwater flow on the swelling of the Gipskeuper formation in the Chienberg tunnel*	2012
1386	VSS 2006/204	Schallreflexionen an Kunstbauten im Strassenbereich *Réflexions du trafic routier aux ouvrages d'art* *Noise reflections on structures in the street*	2012
1387	VSS 2010/205_OBF	Ablage der Prozessdaten bei Tunnel-Prozessleitsystemen *Data storage in tunnel process control systems* *Enregistrement ds données de systèmes de supervision de tunnels*	2012
649	AGB 2008/012	Anforderungen an den Karbonatisierungswiderstand von Betonen *Exigences par rapport à la résistance à la carbonatationdes bétons* *Requirements for the carbonation resistance of concrete mixes*	2012
650	AGB 2005/010	Korrosionsbeständigkeit von nichtrostenden Betonstählen *Résistance à la corrosion des aciers d'armature inoxydables*	2012