Construction and Building Materials 102 (2016) 455–461

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Pavement stiffness measurements in relation to mechanical impedance

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HIGHLIGHTS

- Relationship between mechanical impedance and stiffness of road surface is investigated.
- Mechanical impedance and stiffness of different types of pavements are measured.
- Mechanical impedance is measured by an impedance hammer method both in laboratory and on field.
- Statistical relationship between impedance and stiffness of road surface is developed.
- Suggestions are given for noise reducing pavement development by considering mechanical impedance.

ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 16 October 2015
Accepted 28 October 2015
Available online 13 November 2015

Keywords:
Mechanical impedance
Stiffness
Resilient modulus
Thin layer surfacing
Tyre–road noise

ABSTRACT

The mechanical impedance is a measure of the ability of a structure to resist motion when subjected to a given force. It has been considered related with tyre–road noise level of road surface. However, this parameter is seldom used to characterize mixtures in asphalt mixture design. In this study, the relationship between the mechanical impedance and the pavement stiffness is investigated based on laboratory and in-situ measurements. Mechanical impedance is tested by an impedance hammer device, while the stiffness is measured by the indirect tension test (ITT) method. Different types of road surfaces are taken into account, including thin layer noise reducing surfacing, dense surface and poro-elastic road surface. The influences of mixture compositions on mechanical impedance and stiffness are discussed. Statistical relationship between the stiffness and the mechanical impedance is developed based on the measurement results. Advices for noise reducing road surface design by considering mechanical impedance are given according to the research findings.

1. Introduction

Mechanical impedance is defined as the ratio of the force acting on a structure to the resulting displacement velocity of the system [1]:

$$Z = \frac{F}{v} \tag{1}$$

where F is the complex force vector and v the complex velocity vector. Mechanical impedance measures the ability of the structure to resist motion caused by the force.

In road engineering, mechanical impedance has received increasing attention as a parameter which influences the tyre–road noise in the medium frequency (630–1600 Hz) [2,3]. In an experiment undertaken by Dutch researchers, coast-by noise measurements were carried out on a concrete surface and on an elastic layer with similar surface texture glued on the same type of concrete surface. A substantial noise reduction from 3 dB to 5 dB was found in the 800–1600 Hz frequency range by adding the elastic layer [4]. Mechanical impedance is also considered as input for predicting tyre–road noise in hybrid models, such as Acoustic Optimization Tool (AOT) [5,6].

In previous research, the influence of the mechanical impedance on tyre–road noise has been investigated [7]. However, in pavement engineering and asphalt mixture design, the mechanical impedance is never used to characterize mixtures. The commonly used parameter for denoting the mechanical properties is stiffness (S) which is defined as the ratio of applied force (F) to resulting displacement (D) and given in Eq. (2):

$$S = \frac{F}{D} \tag{2}$$

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http://dx.doi.org/10.1016/j.conbuildmat.2015.10.191

It is of importance to relate the mechanical impedance with the stiffness. In this way, the mechanical impedance can possibly be related to stiffness tests which are regularly done in mixture design and evaluation. Such a relationship would be very useful and helpful for pavement engineers, as they can deduce the mechanical impedance from the given stiffness without carrying out special test work.

In this research, laboratory measurements and in-situ measurements were performed for investigating the mechanical impedance and stiffness on different types of road surface. The relationship between the stiffness and the mechanical impedance was the discussed. In the end, it came up with an advice on how to achieve the tyre–road noise reduction based on mechanical impedance in pavement design.

2. Materials and measurement methods

2.1. Materials

2.1.1. Thin layer surfacing

In this study, most of the work was taken on thin layer road surfacing. Thickness of this type of road surface is generally between 20 mm and 30 mm. It is a typical noise reducing pavement which aroused concern in Europe in recent years [8,9]. It was considered to be a replacement of the commonly used porous asphalt, noise reduction ability of which decreases significantly due to clogging of the air voids [10,11]. In this research, the thin layer surfacings for measurements were from two sources:

(1) Laboratory produced slab samples with different mixture composition. The size of the samples is 700 mm × 500 mm, with a thickness 30 mm. The mixture compositions of the slab samples are given in Table 1. The binder used in P06 is colorless bitumen Sealoflex Color with addition of Bayferrox synthetic iron oxide pigments. All the other mixtures were made of Cariphalte DA. Properties of the two types of bitumen are given in Table 2.

(2) Kloosterzande trial sections in The Netherlands: These trial sections are located in the most northern part of the N60 road in The Netherlands. 40 sections with different surface types were laid in the year 2005 and 2007 respectively [12]. The thin surfacings involved in this study are shown in Table 3. The designed thickness is 25 mm.

2.1.2. Other materials

In addition to thin layer surfacing, the tests were carried out on a dense asphalt surface layer and a poro-elastic surface (Roll Pave) in Kloosterzande sections [11]. Material properties of these two surfaces are quite different from the thin layer surfacings. The dense layer is a standard ISO surface with a coarse aggregate size of 0/8 mm and a designed thickness of 30 mm. The poro-elastic surface comprises fine aggregate and rubber particles, which works in increasing elasticity of the surface. The air voids content is around 30% [11].

2.2. Measurement methods

2.2.1. Mechanical impedance measurement

As mechanical impedance is a newly considered influential parameter on tyre–road noise, there is no existing standard method to determine this parameter. Generally speaking, it can be measured by applying an impact to the road surface and recording the response of the material in terms of its vibration. In existing studies, test with an impedance hamper was commonly used [4]. The method is also introduced in this research. A measurement on the road surface is illustrated in Fig. 1. The measurement process and data proceeding methods are described in a previous work by the authors [13]. The tests are conducted at an ambient temperature around 20 °C. It should be noted that the velocity is tested at different positions

Table 1
Mixture compositions of laboratory produced thin layer surfacings.

	Coarse aggregate content (% by mass)	Max. Aggregate size (mm)	Air voids content (% by volume)	Binder content (% by mass of mixture)	Aggregate type
Ref.	78	2/6	12	6.1	Bestone
P01	78	2/6	8	6.1	Bestone
P02	78	2/6	18	6.1	Bestone
P03	72	2/6	8	6.1	Bestone
P04	68	2/6	8	6.1	Bestone
P05	78	4/8	12	6.1	Bestone
P06	78	2/6	12	6.1	Tillred
P07	78	2/6	12	6.1	Irish Greywacke
P08	78	2/6	12	7	Bestone

Table 2
Binder properties of the investigated thin layer surfacings.

Items	Cariphalte DA	Sealoflex color
Penetration, at 25 °C, unit: 0.1 mm	85–130	70–100
Ring and ball softening point, unit: °C	⩾80	50–56

Table 3
Basic information of the mixtures used in the Kloosterzande test sections.

Trial section no.[a]	Coarse aggregate content (% by mass)	Air voids content (% by volume)	Binder content (% by mass of 100% aggregate mass)	Thickness (mm)
2	47	12	7.2	25
3	65	8	7.8	25
4	74.8	12	7.5	25
5	72.5	12	6.6	25
9	86	>20	6.0	25
15	78.8	>20	6.0	25

[a] Numbers of the sections are in accordance with the original numbers of the trial sections.

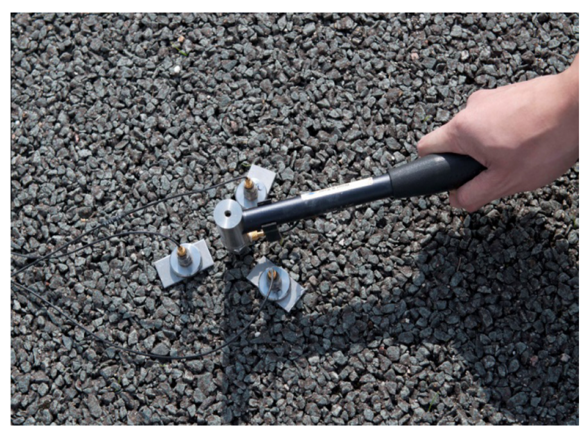


Fig. 1. Impedance hammer test on the road surface of trial sections.

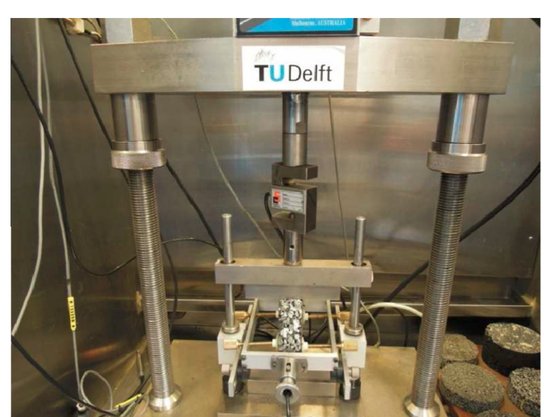


Fig. 2. Setup of the cyclic ITT in the laboratory.

from the point where the driving force is applied. The calculated results are therefore considered as mechanical transfer impedance. The most important influencing factor on mechanical transfer impedance is the distance between the accelerometer and the point where the force is applied. For better measuring the surface reaction to the hitting and providing enough space for the hit, the center distances between each two sensors is set as 6.5 cm [13].

2.2.2. Stiffness measurement

Several standardized laboratory test methods are available for measuring the dynamic modulus of asphalt mixes, such as bending, direct tension–compression and cyclic indirect tension tests (ITT) [14]. In this study, the cyclic 5 pulse ITT method is used for determining the resilient modulus of the thin layer surfacing cores. The equipment used is a Universal Testing Machine (UTM). The device with mounted sample is shown in Fig. 2. Measurement procedure refers to the specification NEN EN12697-26 [14].

The ITT tests were performed on the cores which three of them were drilled from the slab thin samples, and two from the Kloosterzande sections. The diameters were all 100 mm.

3. Mechanical impedance test result analysis

A summary of the mechanical impedance of all the slabs tested in the lab is illustrated in Fig. 3. It can be seen that the mechanical impedance for the different mixtures is close to each other below 1000 Hz. The differences mainly occur at between 1500 Hz and 3000 Hz, and the reasons for the differences are analyzed in the previous work [13].

It should be noted that there is a resonance in the curves between 1500 Hz and 2000 Hz does not reflect the mechanical impedance of the slab. According to a previous study [4], the frequency band which is of interest for tyre–road noise lies between 500 Hz and 2000 Hz. This means there is lack of information on the important frequencies in the spectral analysis. Therefore, a new indicator for the mechanical impedance is proposed in this study.

As known the stiffness is the ratio between maximum force applied and the resulting maximum displacement. In analogy with the stiffness, the new indicator of mechanical impedance (MI′) is defined as the ratio of maximum force to the maximum resulting velocity. Fig. 4 shows the curves of the force and the velocity which is obtained by integration of the acceleration signal [13]. The maximum force and the maximum velocity can be achieved from the curves. MI′ is thus calculated by:

$$MI' = \text{Max.Force}/\text{Max.Velocity} \tag{3}$$

It should be noted that there is a time lag between the moments when maximum force is measured and the maximum velocity of the surface is recorded. However, the time lag is much short which is less than 10^{-5} s and difference of the velocity shown at the two

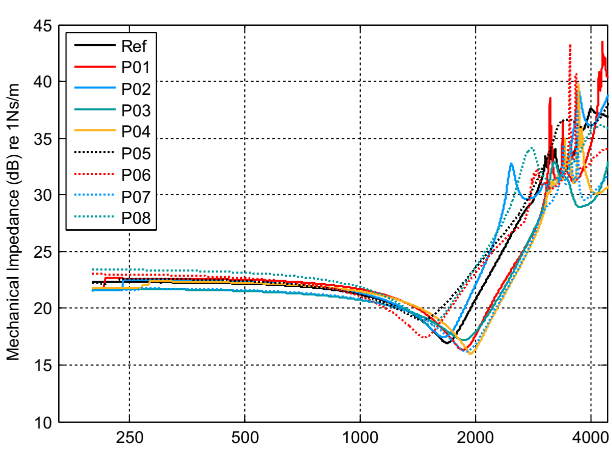


Fig. 3. Mechanical impedance of thin layer surfacing slab samples.

moments is also small, less than 10^{-4} m/s. The very little difference of time and velocity value influences less on the calculation of MI′. Moreover, The Max.Velocity is considered the largest response of the road surface caused by the Max.Force. Therefore, it is reasonable to introduce the MI′ to describe the mechanical impedance.

The mechanical impedance expressed by MI′ is calculated for the slab samples and test results on Kloosterzande sections, as plotted in Fig. 5. As two tracks were constructed with each type of material (as shown in Table 3), the test was conducted on each track separately. Results from the both tracks are shown in Fig. 5. For example, tests on the two tracks with material No. 2 are numbered 2-1 and 2-2 in the figure.

By comparing the results obtained on the different surfaces, it can be seen that the mechanical impedance of the concrete floor is the highest, while the lowest value is found on the poro-elastic surface. The slab samples show very similar MI′ values.

The MI′ values of all the Kloosterzande sections, including the thin layer surfacings and the dense surface, are comparable. However, the mechanical impedance of asphalt surfaces on Kloosterzande sections is higher than those of slab samples. It indicates that the in-situ road surface has a higher resistance to motion compared to the slabs produced in the lab. The explanation is that the surfaces in practice are well compacted by a roller compactor and consequently have a more stable structure. Also, the surface area of the in-situ sections is much larger than that of the slab. And the real road has a multi-layer structure composed of a top layer, base layer and a sub-grade. For the slab samples, the surface area is limited and the boundaries are different from the road surface. The slab is not glued to the ground underneath. These placement conditions of the slabs might make slabs more easily to vibrate than the real road surface.

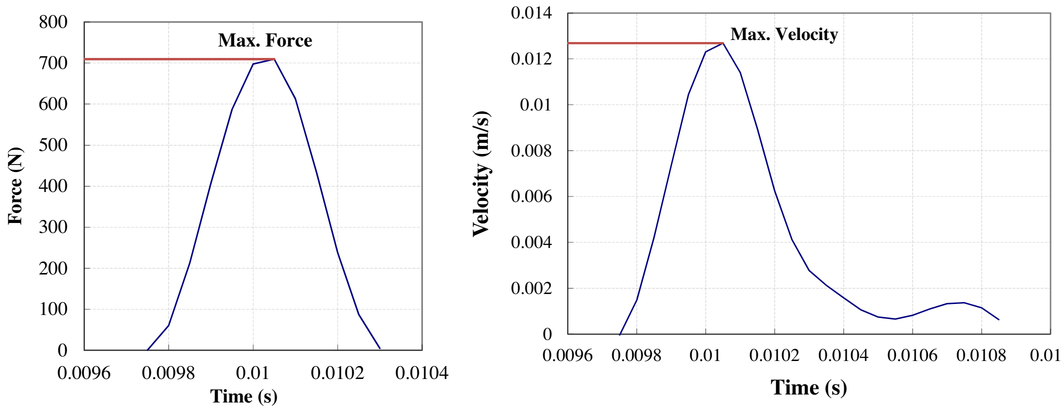
4. Stiffness measurement results analysis

The stiffness test was performed by means of the ITT method at 5 different temperatures being 5, 10, 15, 20, 25 °C. The master curves of the resilient modulus were generated based on the test results obtained at different temperatures and loading frequencies [15]. As the mechanical impedance is measured at 20 °C, a reference temperature of 20 °C is chosen to construct the resilient modulus master curves. As three cores were extracted from each slab, the master curve for the slab is based on the average modulus of the three cores. The frequency range for the curves is from 0.1 Hz to 2000 Hz. The resilient modulus in relation to mixtures composition is illustrated in Fig. 6. The master curves for samples with different material properties are in general close to each other.

Fig. 6(a) shows the influence of the air voids content on the resilient modulus. It indicates that the influence of the air voids content on the stiffness is not obvious for materials with high air voids content, in this case higher than 12%. The stiffness above 10 Hz increases when the air voids content decreases to a certain level, e.g. 8%.

Fig. 6(b) compares the resilient modulus of samples with various coarse aggregate volumetric contents. The designed air voids of the samples are all equal to 8%. It shows that the stiffness increases with increasing coarse aggregate content. This is because a more stable skeleton is achieved by using a large percentage of aggregates, and smaller deformations will be caused by the loads.

Fig. 6(c) shows that the modulus of two specimens with a different maximum aggregate size is almost the same in the frequency range above 100 Hz. At frequencies lower than 100 Hz, the resilient modulus of the cores with a coarse aggregate size of 2/6 mm is higher than that of the cores with 4/8 mm as maximum



(a) Force (b) Velocity

Fig. 4. Curves of fore and velocity in an impedance hammer test.

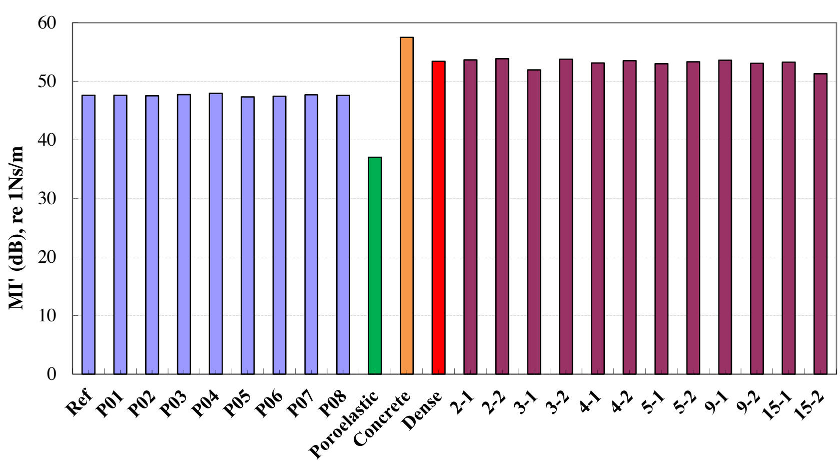


Fig. 5. Mechanical impedance for different surfaces.

aggregate size. This is because the lower frequency corresponds to a high temperature in the stiffness test [16]. The bitumen works less at high temperature. The 2/6 mm aggregates in the mixture are better connected than 4/8 mm aggregates because of the smaller size. Thus the 2/6 mm aggregates are considered better interlocked and has more resistance to deformation.

The effect of aggregate types is shown in Fig. 6(d). Ref and P07 show almost the same resilient modulus which is higher than that for P06. It seems that the aggregate type has influence on the stiffness. However, it is much more likely the bitumen has more influence. As shown in Table 2, both types of bitumen do not have the same penetration and softening point, so the stiffness is also different correspondingly.

Fig. 6(e) shows that a lower stiffness is obtained by increasing the binder content by 1%; this is in agreement with common knowledge.

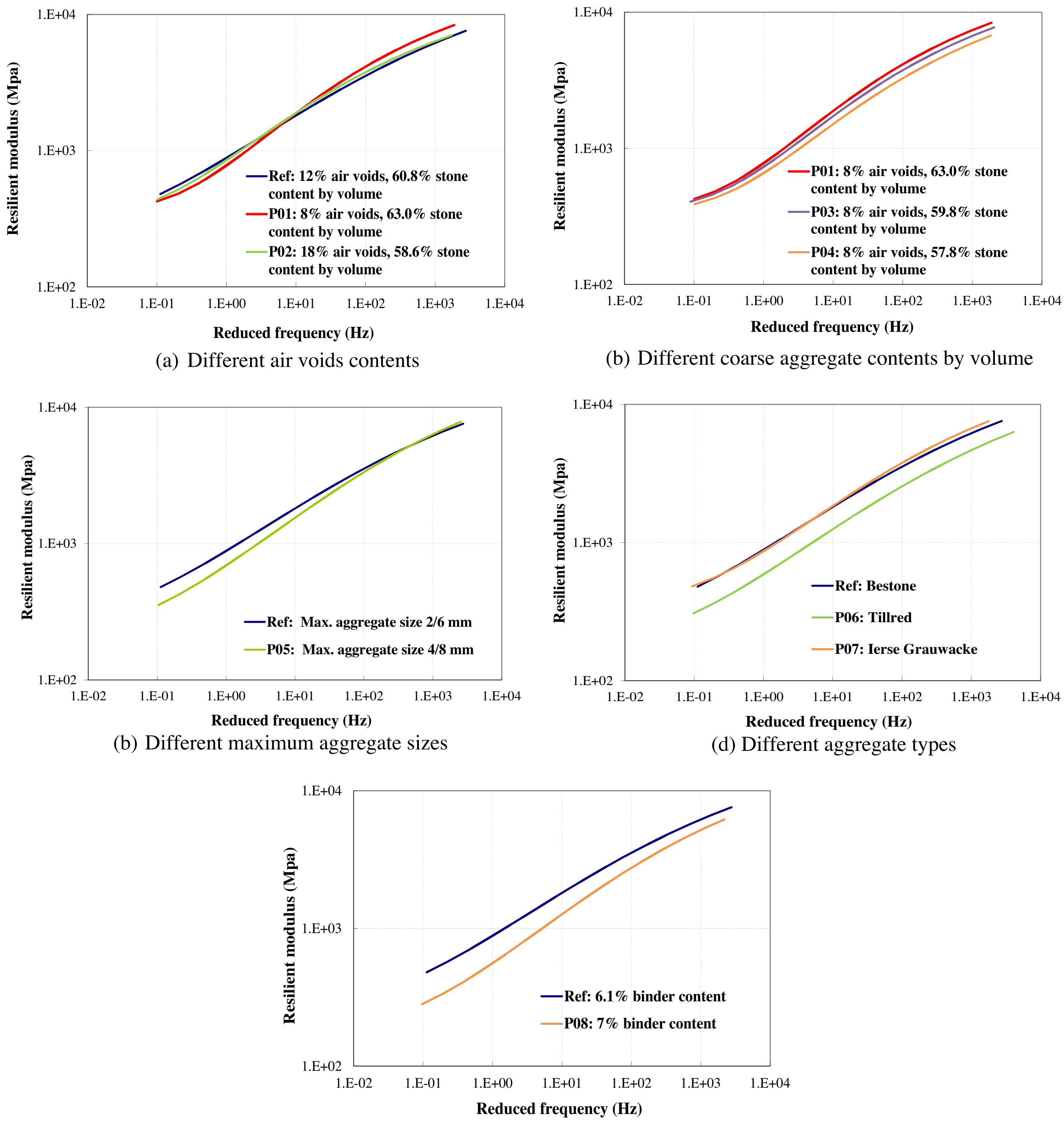
Fig. 7 compares the master curves at 20 °C of all the road surfaces taken into account in this study. The figure clearly shows the differences in stiffness between concrete, asphalt and poroelastic surfaces. The cement concrete shows the highest resilient modulus in the whole frequency range, followed by the surfaces from Kloosterzande, the thin layer surfacing slabs and the poroelastic surface, in a descending order. The curves for asphalt mixtures from the same source (e.g. Kloosterzande or slabs) are close to each other. More specifically, thin layer surfacings from the Kloosterzande sections have almost the same resilient modulus. The stiffness values of the slab samples are also close but they are lower than those from the Kloosterzande sections. The trends coincide with the observations made on the mechanical impedance data.

5. Relationship between mechanical impedance and stiffness

By comparing the MI′ values and the resilient modulus shown in Figs. 5 and 7 respectively, significant differences of mechanical impedance are only observed between materials with a large difference in stiffness.

In this section, the specific relationship between the mechanical impedance and stiffness is explored based on the data from both the impedance hammer and resilient modulus tests. The MI′ is used as a representative parameter for the mechanical impedance. In terms of stiffness, the resilient modulus at certain frequencies is selected in the analysis. As the mechanical impedance ranging from 500 Hz to 2000 Hz influences the tyre–road noise most, in this study, the resilient modulus values at 500 Hz and 2000 Hz are used for denoting the stiffness at medium and high frequency respectively.

Fig. 8 shows the MI′ values against the resilient modulus. Regression relationship is developed, with the regression equation and the trend line shown in the figure. It can be seen that the MI′



(a) Different air voids contents
(b) Different coarse aggregate contents by volume
(b) Different maximum aggregate sizes
(d) Different aggregate types
(e) Different binder contents

Fig. 6. Master curves of the resilient modulus of slab samples (20 °C).

value is linear related with the logarithm of the resilient modulus at 500 Hz and 2000 Hz respectively. According to the regression trend line, the MI′ value is sensitive to the stiffness when the stiffness of the material is low. As shown in the figures, when the resilient modulus is below 5000 MPa, MI′ dramatically decreases with reducing resilient modulus. From 5000 MPa to 30,000 MPa, MI′ slowly increases.

According to existing research, a larger mechanical impedance tends to result in a higher tyre–road noise level [7]. From a noise reduction point of view, a road surface with low mechanical impedance is appreciated. This study shows that a low mechanical impedance coincides with a very low stiffness. For an asphalt road surface, it is difficult to improve the noise reduction based on the mechanical impedance. The good relation between mechanical impedance and stiffness however shows that an effective way to obtain a low mechanical impedance is to use materials with a very low stiffness, such as poro-elastic materials, with stiffness value lower than 150 MPa in the whole frequency range (as shown in Fig. 7). As the mechanical impedance is not a parameter that is regularly used, the regression equations derived in this study are suggested to be applied to estimate the mechanical impedance from the stiffness of a material.

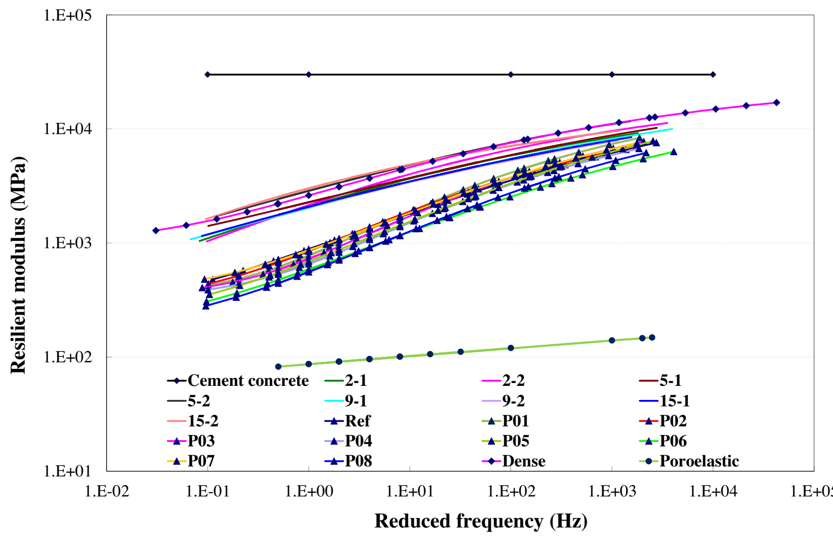


Fig. 7. Master curves of resilient modulus for different types of road surface samples (20 °C).

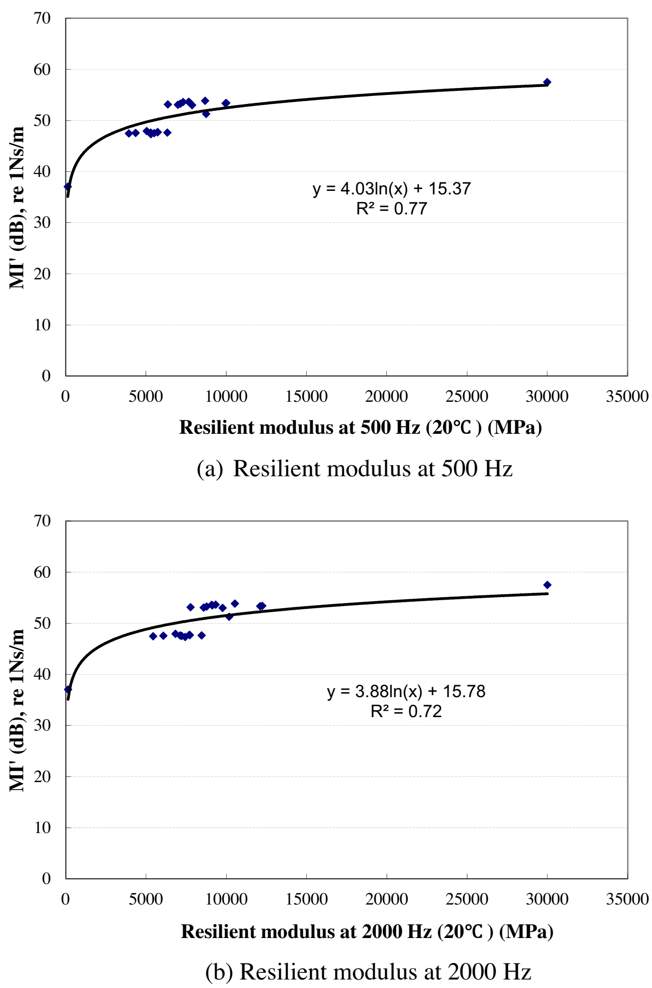


Fig. 8. Relationship between mechanical impedance and resilient modulus.

6. Conclusions and recommendations

Mechanical impedance tests with the impedance hammer setup were carried out on the slabs and the trial sections. Furthermore the resilient modulus as a denotation of pavement stiffness was measured with ITT method. In addition to thin layer surfacings, also a dense asphalt concrete mixture and a poro-elastic surface layer were involved in the measurements.

The test results showed that the cores from the road sections have comparable mechanical impedance while slab samples made in the lab also have a similar mechanical impedance. But there are differences between samples from these two sources. The difference in mechanical impedance of materials is only significant when there is a significant difference in stiffness. The regression analysis showed that mechanical impedance is linearly related to the logarithm of the resilient modulus.

For development of the noise reducing pavement based on mechanical impedance, an effective way is to reduce the mechanical impedance by using very low stiffness materials, such as poroelastic materials. It will not be possible to produce low mechanical impedance layers using standard asphalt concrete mixtures.

In further study, a direct measurement method with the impedance hammer is strongly suggested to be developed which can reflect the direct motion of the surface caused by the force. And the resonance of the system needs to be eliminated by suitable loading mode.

Acknowledgments

The authors would like to thank the help and technical support of Ir. G. Gaarkeuken from BAM Groep nv and Mr. Peter The from Rijkswaterstaat in The Netherlands. The authors also would like to thank Ballast Nedam b.v. and Rijkswaterstaat in The Netherlands for providing the thin layer surfacing materials and giving advices.

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