DELIVERABLE D5.18

CONTRACT N° **TIP4-CT-2005-516420**
PROJECT N° **FP6-516420**
ACRONYM **QCITY**
TITLE **Quiet City Transport**

Subproject 5 **Implementation of measures at validation sites**
Work Pack 5.5 **Validation of measures for Göteborg**

Couple mechanical and propagation models to predict far-field sound - with emphasis to define methods for determination of sound absorption characteristics of open graded road surfaces

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Date of issue **2009-01-30**

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PROJECT START DATE **February 1, 2005**
DURATION **48 months**
Project funded by the European Community under the SIXTH FRAMEWORK PROGRAMME
PRIORITY 6
Sustainable development, global change & ecosystems

This deliverable has been quality checked and approved by QCITY Coordinator
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TABLE OF CONTENTS

0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The object of this deliverable is to define methods for determination of the sound absorption properties of an open graded sound absorbing road surface with the aim of predicting its sound radiation and/or sound propagation characteristics.

0.2 STRATEGY USED AND/OR A DESCRIPTION OF THE METHODS (TECHNIQUES) USED WITH THE JUSTIFICATION THEREOF

The strategy used is to avoid complicated correction for spherical wave propagation (such as would prevail if a small sound source is positioned rather close to the road surface) by ensuring that incident wave field essentially consists of plane waves. This is done by using sound sources with enough overall dimensions, producing a coherent and essentially plane wave field over its sound transmitting surface.

0.3 BACKGROUND INFO AVAILABLE AND THE INNOVATIVE ELEMENTS WHICH WERE DEVELOPED

The innovative elements in this Deliverable are to combine a plane incident wave field with a PU-probe in order to directly determine the absorption coefficient of a sound absorbing road surface at desired angles of incidence. Ensuring a plane incident wave field would make complicated and tedious corrections for spherical to plane wave field unnecessary. Such corrections would also substantially increase the uncertainty of the presented data, since the $\lambda/4$-resonance that easily can be determined from measurements of sound absorption factors at normal incidence is not present when measuring the absorption factor at oblique incidence typical for the tyre/road system. A method for measuring the absorption factor at "correct" angles would be very important for arriving at the correct optimization conclusions regarding low noise road surfaces.

0.4 PROBLEMS ENCOUNTERED

The main problem is to create the plane wave field. This is a problem both with respect to the dimensions of the sound source as well to phase match the different loudspeaker elements if an array speaker is used as a source.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

ACL is the only partner involved in the production of this Deliverable.

0.6 CONCLUSIONS

Equations governing the sound absorption from granular materials have been created and processed. Various methods to determine the sound absorption coefficient of porous road surfaces have been discussed and evaluated.

It has been judged that the best way of measuring the sound absorption coefficient at desirable angles of incidence was:

1) to ensure an oblique incident plane wave to the sound absorbing surface during field measurements and

2) to use a PU-probe (probe that simultaneously measures the sound pressure and the particle velocity of a stationary sound field) or to use just one single microphone (that measures impulse sound) for determination of the physical parameters necessary to calculate the sound absorption coefficient at desired angles of incidence.

A complete laboratory method has been developed to determine the sound absorption coefficient for oblique incidence of plane waves against porous road surfaces (thus a second best method). This method is based on absorption measurements in Kundt's tube (normal incidence) on porous road surface samples (e.g. "rubberized asphalt") and a set of equations, which convert the measured absorption coefficient (normal incidence) to corresponding absorption coefficient for oblique incidence assuming plane waves. A dimensionless simple sound absorption **Index** has been created for ranking and optimization of different porous samples.

However, this method is based on laboratory road samples in Kundt's tube, which might be cut out of real road surfaces or just manufactured for laboratory tests. Thus, the method can not be used for corresponding direct field measurements of the sound absorption coefficient for oblique incidence. The proposed measurement method for field determination of road surface sound absorption at oblique wave-field incidence is thus important because it provides possibilities for non-destructive and direct evaluation of the sound absorption factor for "correct" angles.

0.7 RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)

This deliverable D5.18 has direct relation to the D5.5 which deals with the poroelastic open, sound absorbing and compliant surfaces that has been developed together with the QCITY partners TRAF (Trafikkontoret Göteborg) and NCC (a major Swedish road contractor).

1 INTRODUCTION

With the increased used of open graded, sound absorbing road surfaces, there has also emerged a need for rapid and precise determination of the sound absorption factor at desirable radiation angles[1]. With such a method, a tool is available both for verification of existing low-noise surfaces including its possible long term degradation as well as means for predicting and optimizing the sound absorption of open-graded low-noise surfaces.

The amplification effect of sound, radiated from the leading and trailing contact edge of the tyre/road system, is active from 800 Hz and upwards, in frequency. This is caused by the horn-shaped geometry between the tyre and road surface. Therefore the influence of porous road surface sound absorption can be quite substantial. The mechanism for noise reduction through road surface sound absorption is primarily that one of the “walls” of the tyre/road horn will be “partially eliminated”, which then destroys the amplification effect. This reduces the total sound power radiated from the tyre/road horn which is due to the decrease in radiation impedance of the tyre tread band vibration sources[2] in this area.

However, the reduction of radiated sound is much different from what can be concluded of the sound absorption coefficient for normal incidence of plane waves as measured in an impedance tube (or Kundt’s tube) on samples of porous road surfaces. Most of the sound from the tyre/road system is radiated in smaller angles than normal down to about 15 - 60 degrees (averaging around 40 degrees). It would therefore be convenient if the sound absorption coefficient versus frequency could be measured **in situ** at the appropriate radiation angles (e.g. at an average angle of around 40 degrees) for a more correct comparison or just ranking of the sound absorption coefficients of different road surfaces. Another advantage of using this quantity is that it is independent of the various tyre/road sound source and coupling conditions. Thus, two different measurement devices (“parabolic reflector” and “loudspeaker array”) for in situ measurements of the sound absorption coefficient versus frequency at any appropriate radiation angle are proposed and presented in this deliverable.

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[1] This is of particular importance since resonance peaks present for measurements at normal incidence (such as in an impedance tube) will be far from fully excited for the oblique incidence typical for tyre/road systems.

[2] The tread band vibrations seen as a source of sound would be of a «*constant velocity type*».

An approximate method has been developed to calculate the sound absorption coefficient for oblique incidence (i.e. at any appropriate radiation angle) of plane waves against **samples** of porous road surfaces. This method is based on absorption measurements in Kundt's tube (normal incidence) on porous road samples (e.g. "rubberized asphalt") and a set of equations, which convert the measured absorption coefficient of the road sample to an estimated absorption coefficient for oblique incidence against corresponding **in situ** road surface at any selected angle assuming plane waves. The main features of this method are described in this deliverable.

Significant intermediate results of these set of equations are the 'specific flow resistance', the 'speed of sound and the 'specific wave impedance' of the porous road surface layer. They represent fundamental (independent) acoustic properties of this layer, which are appropriate input data for acoustic calculations (e.g. FEM, BEM) on the tyre/road system (the absorption coefficient is not usable in such calculations). Such acoustic input data can also be calculated from measured absorption coefficients of in situ measurements with the above mentioned devices ("parabolic reflector" or "loudspeaker array").

SP5, D5-18
Methods to assess absorption of open pore asphalt from far field measurement.
Use of sound intensity probe (PU probe).
What about the Adrienne methods for sound absorption of noise barriers, which is also supposed to work under correct angles?

Thank you for providing the Adrienne reference. However, one of our prime findings was that the wave field must be plane in the entire frequency region studied in order to arrive at absorption coefficients, which are not influenced by the test conditions. Such coefficients and related quantities (i.e. flow resistance, specific wave impedance and speed of sound) can be used for ranking of different poroelastic road surfaces and as input data for advanced acoustic calculations of the tyre/road system.

By looking at the pictures in reports from the Adrienne project it is revealed that only point sources have been used. Therefore, it may be concluded that the project was not able to grasp the point that plane waves must be generated in order to achieve corrects results. In order to obtain plane wave the sound source must (as you already know), among other characteristics, have a physical size that should be comparable to the wave-length for the lower limiting frequency of the measurement.

Lately, various methods have been discussed and investigated regarding direct field measurements of the sound absorption coefficient for oblique incidence of plane waves against porous road surfaces. The main findings from these discussions and investigations are presented in this deliverable.

Earlier in the QCITY project, a reciprocity method has been developed for direct quantification of the reduction spectrum resulting from any selected combination of tyre/road design. However, the advantage of using the sound absorption coefficient instead of the reduction spectrum obtained by the reciprocity method is that the sound absorption coefficient will give results that are road surface oriented (i.e. describes a property of the road surface only) and thus independent of any tyre dimension (i.e. width and diameter) and/or tyre tread design.

Coupling between mechanical and acoustical characteristics could possibly be obtained e.g. by deformation of the road surface in the contact patch area. The *coupling* would then occur by reducing the void content in the contact area relative to the void content outside the contact area. However the maximum deflection of the up to now tested compliant road surfaces during passage of the tyre relative to a normally stiff road surface would only be around 0.1 mm, which is judged not to be enough to produce any significant reduction of the void content causing any increase in noise reduction. A further increased compliance of the road surface, so that contact deflections around 1 mm would be obtained, could possibly result in some coupling effects with possible increase in tyre/road noise reduction. It is though debatable if a road surface with such high compliance would be feasible with respect to wear, vehicle dynamics etc.

2 LABORATORY MEASUREMENTS OF SOUND ABSORPTION

2.1 INTRODUCTION

A laboratory method has been developed to determine the sound absorption coefficient for oblique incidence of plane waves toward porous road surfaces. This method is based on absorption measurements at normal incidence in an impedance tube (Kundt's tube) on samples of porous road surfaces (e.g. "rubberized asphalt") and a set of equations, which convert the measured absorption coefficient at normal incidence to corresponding absorption coefficient for oblique incidence assuming plane waves. The main features of this method are described in this chapter.

2.2 MEASUREMENTS IN KUNDT'S TUBE ON POROUS ROAD SAMPLES

The sound absorption coefficient versus frequency at normal incidence of a plane wave against any porous road sample can be measured in Kundt's tube.

A typical specification for a measurement device is as follows:

Impedance tube:	Brüel & Kjær typ 4206 (diameter 100 mm)
Frequency range:	50 Hz - 1600 Hz
Microphones:	Brüel & Kjær type 2660
Amplifier:	Labgruppen LAB 500
Analyzer:	Brüel & Kjær PULSE frontend type 3560 C
Software:	Brüel & Kjær PULSE LabShop version 12.5

In figure 1 some porous samples are shown as well as a typical measurement set-up with the impedance tube (Kundt's tube).

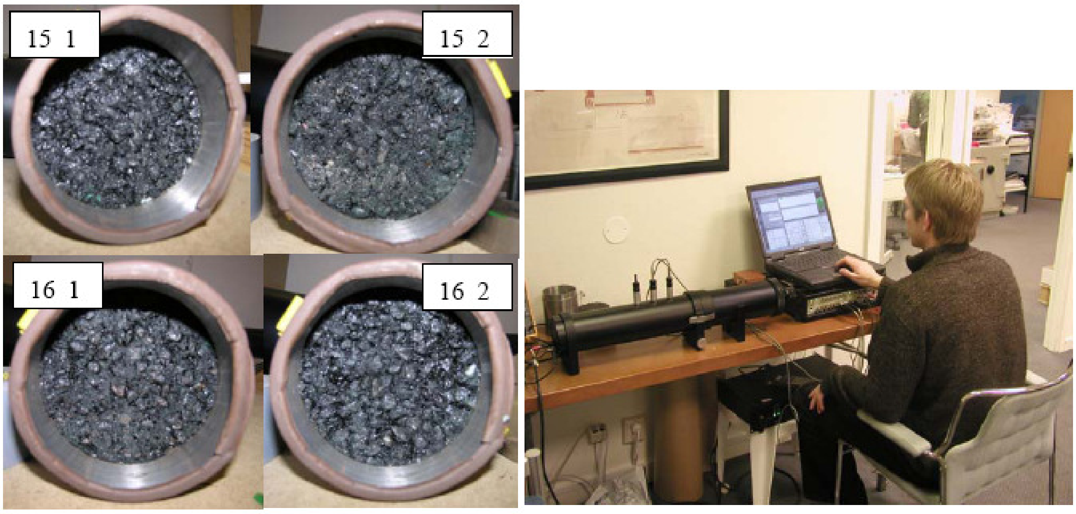


Figure 1 *Samples of porous road surfaces and measurement set-up with the impedance tube (Kundt's tube)*

The porous samples must be carefully sealed to the tube bottom and wall. If the porous samples are not sufficiently sealed, then the measured sound absorption will be corrupt.

In figure 2 sound absorption coefficients are illustrated for some porous samples.

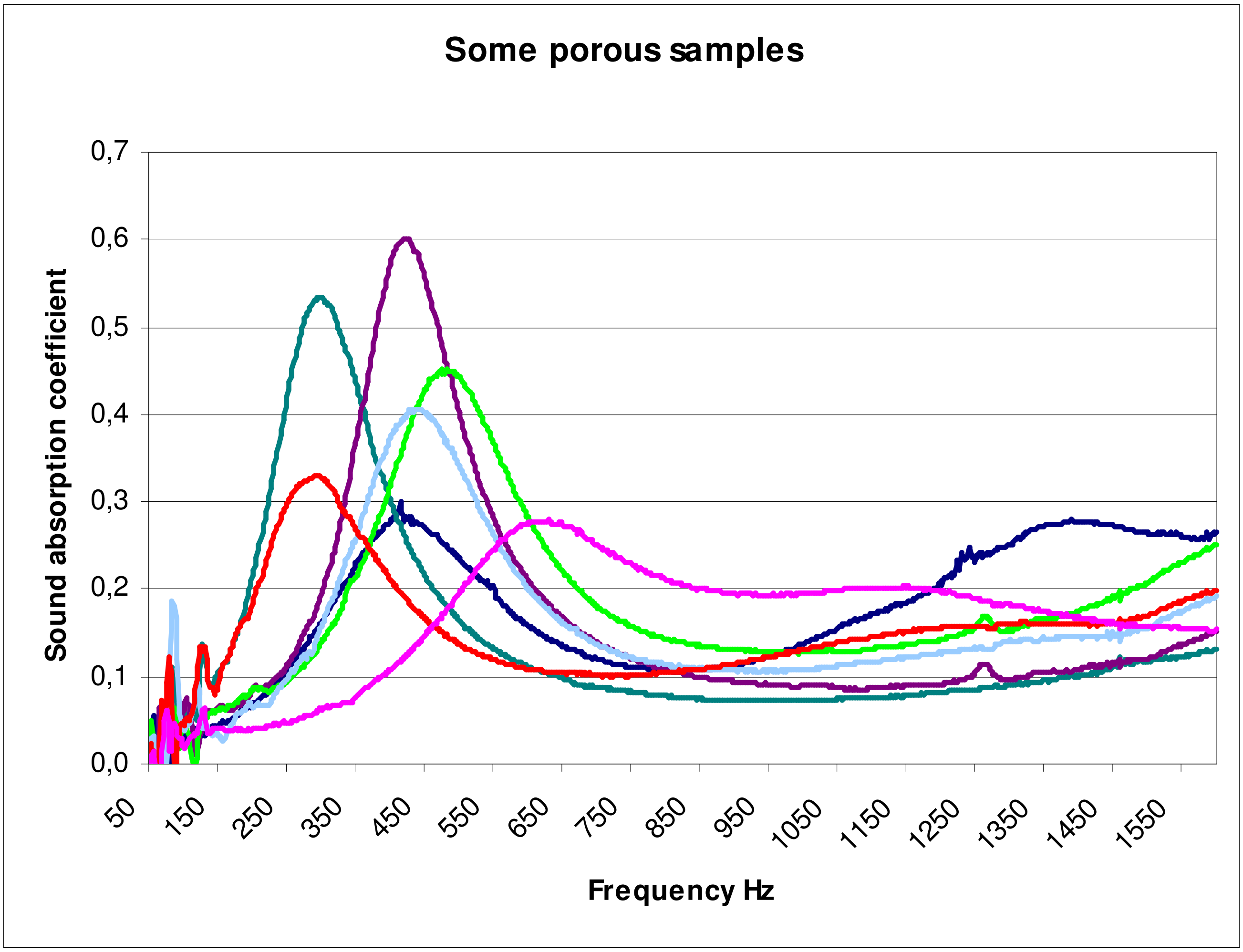


Figure 2 *Measured sound absorption coefficients versus frequency at normal incidence of plane waves against some porous road samples.*

The peaks in figure 2 (within 250 – 750 Hz) represent λ/4-resonances in the thickness direction of each sample. For plane waves at normal incidence, this λ/4-resonance peak will reach its maximum (by wave interference).

However, for plane waves at *oblique* incidence (e.g. 45 degrees), these peaks will be more or less "broken down" to a fairly straight line as indicated by the calculated blue curve in figure 4. The reason for this difference with respect to the λ/4-resonance peak is that the resonance is fully excited and developed for the pure normal incidence. At oblique incidence e.g. at 35-45 degrees this resonance will be only weakly excited.

2.3 CONVERSION OF NORMAL TO OBLIQUE INCIDENCE ABSORPTION

The calculated sound absorption coefficient versus frequency at oblique incidence (e.g. 45 degrees), for a porous sample (e.g. according to figure 4 "Kärraverket P2"), is based on the corresponding sound absorption coefficient measured in Kundt's tube for normal incident plane waves.

1) The 'specific flow resistance', **2)** the 'speed of sound' and **3)** the 'specific wave impedance' of the porous sample are all needed for calculation of the sound absorption coefficient versus frequency at oblique incidence (e.g. 45 degrees).

1) The 'specific flow resistance' is explicitly calculated from a mathematical expression, where the sound absorption coefficient measured in Kundt's tube at the $\lambda/4$-resonance frequency is the only input data needed.

2) The 'speed of sound' is simply identified from the $\lambda/4$-resonance frequency and the sample thickness.

3) The 'specific wave' impedance is identified from a curve-fitting procedure with a mathematical function (SDOF-system = Single-Degree-Of-Freedom) that expresses the absorption coefficient versus frequency around that $\lambda/4$-resonance. This function is illustrated by the example in figure 3 (**blue** curve).

The acoustically related void content of the porous sample (i.e. the percentage of all communicating cavities) can then be calculated from **2)** the speed of sound and **3)** the specific wave impedance.

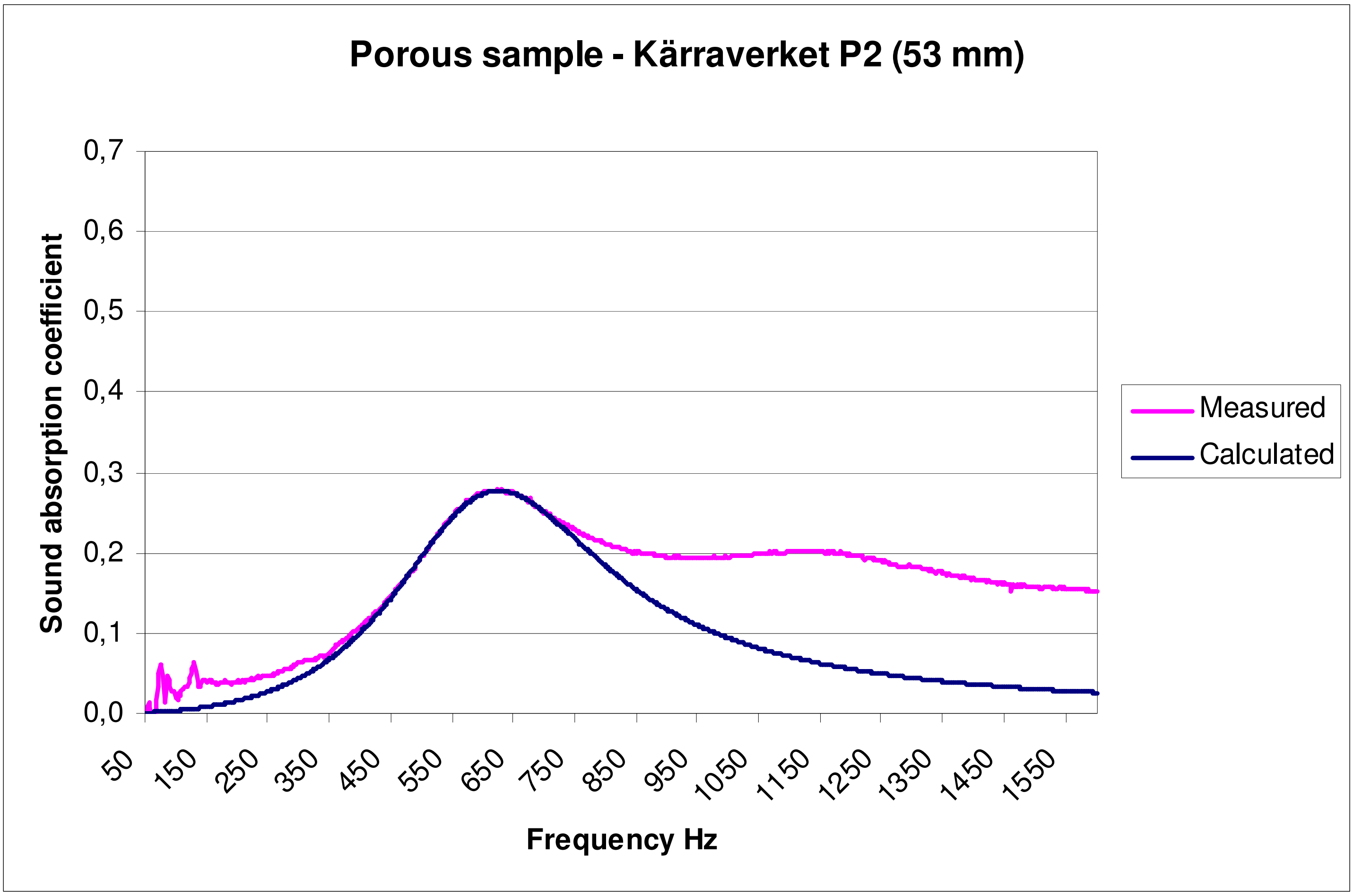


Figure 3 *Example of a measured sound absorption coefficient versus frequency at normal incidence for a poroealstic sample "Kärraverket P2" and corresponding calculated values (curve-fitted) around the $\lambda/4$-resonance frequency of the sample.*

The following acoustic data have been identified for the example of figure 3:

1) Specific flow resistance (Ns/m^4):	3.06*ρc	(ρc = 415 Ns/m^3)
2) Speed of sound (m/s):	0.386*c	(c = 343 m/s)
3) Specific wave impedance (Ns/m^3):	3.10*ρc	(ρc = 415 Ns/m^3)
4) Acoustically related void content (%):	12.5	
- Void narrow paths (%)	3.4	
- Void open cavities (%)	9.1	

2.4 EXAMPLES OF OBLIQUE INCIDENCE ABSORPTION OF POROUS ROAD SAMPLES

Insertion of these acoustic data (1, 2 and 3) and the sample thickness in a set of intensity based equations will result in calculated sound absorption coefficient for plane waves at oblique incidence 45° as illustrated by the blue curve in figure 4.

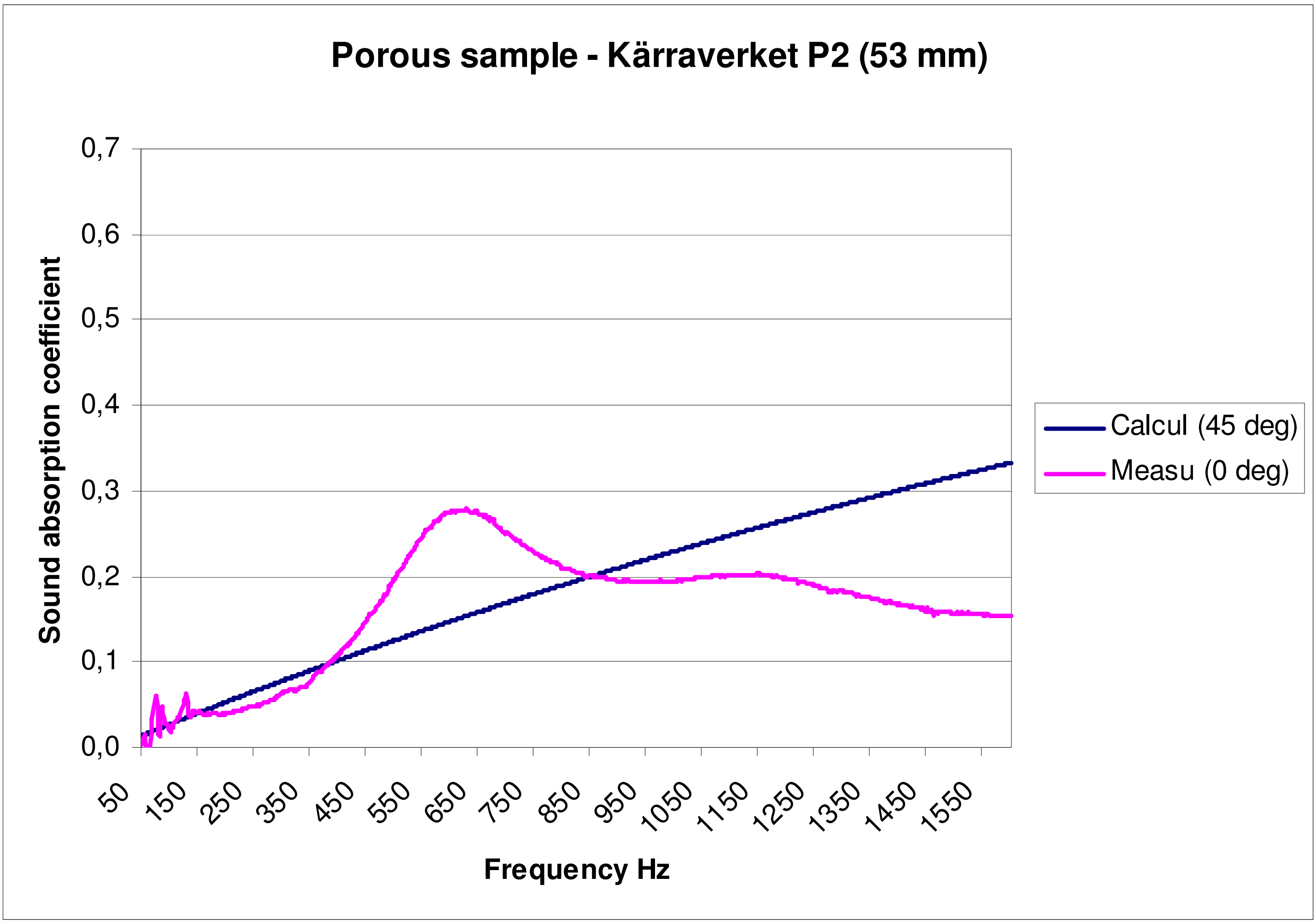


Figure 4 *Example of a measured sound absorption coefficient in Kundt's tube versus frequency at normal incidence for a porous sample "Kärraverket P2" and corresponding calculated values for plane waves at oblique incidence 45°.*

The calculated (45°) absorption coefficient at 1 kHz for this example is **0.23**. This single value is assumed to be representative for the sound absorption properties of that porous sample. If so, it can be used for acoustic ranking of different porous samples.

2.5 CRITERIA FOR RANKING AND OPTIMIZATION OF POROUS SAMPLES

A dimensionless simple sound absorption **Index** has been created for ranking and optimization (the greater the better) of different porous samples as follows:

Index = 50*(frequency)*(Specific flow resistance)*(Sample thickness)^2
/[(Specific wave impedance)*(Speed of sound)] . . . . (1)

It appears that the calculated sound absorption coefficient at 45° and 1 kHz is almost proportional to **Index**, if **Index** <1.5 and less **than** proportional if Index >2. For the example in section 2.4 the sound absorption index at 1 kHz is: **Index** = 50*1000* $3.06*0.053^2/(3.10*0.386*343)$ = 1.05. Thus the calculated sound absorption coefficient **0.23** at 45° and 1 kHz corresponds to a sound absorption **Index** = 1.05. Thus, the sound absorption coefficient at 45° and 1 kHz ≈ 0.2***Index** if **Index** <1.5.

It can be concluded from the sound absorption **Index**, that a greater value of the 'Sample thickness' is most favourable as it is raised to 2. Favourable are also a greater value of the 'Specific flow resistance', a smaller value of the 'Specific wave impedance' and a smaller value of the 'Speed of sound'.

However, the 'Specific wave impedance' and the 'Speed of sound' in the product (Specific wave impedance)*(Speed of sound) are mutually dependent acoustic quantities. This product can be replaced by the following independent design quantities:

(Specific wave impedance)*(Speed of sound) = $(2/\pi)^2$*1.4E5*100*
[(Void narrow paths %)/[(Void open cavities %)*(Total void %)] . . . . (2a)
(Total void %) = (Void narrow paths %) + (Void open cavities %) . . . . (2b)
(Total void %) = 121*(Speed of sound)/(Specific wave impedance) . . . . (2c)
(Void narrow paths %)/(Void open cavities %) ≈ $[(\pi/2)*(\text{Speed of sound})/343]^2$ (2d)

Insertion of (2) in (1) will give:

Index = $(\pi^2/11.2E5)$*(frequency)*(Specific flow resistance)*(Sample thickness)^2
(Total void %)(Void open cavities %)/(Void narrow paths %) . . . . (3)

Increasing the 'Total void %' only according to (3) might be a way of increasing the sound absorption **Index**, but it should rather be combined with an increase of (Void open cavities %)/(Void narrow paths %), thus a decrease of the 'Speed of sound'. Furthermore, such an increase will often result indirectly in a wanted increase of the 'Specific flow resistance' and thereby in an optimization of the **Index**.

3 FIELD MEASUREMENTS OF SOUND ABSORPTION

3.1 INTRODUCTION

Lately, various methods have been discussed and investigated regarding direct field measurements of the sound absorption coefficient for oblique incidence of plane waves against porous road surfaces. The main findings from these discussions and investigations are presented in this chapter.

3.2 SPHERICAL SOUND WAVES

The sound absorption coefficient measured for oblique incidence against porous road surfaces is vary sensitive for the character of the sound field. For example, the spherical sound field generated by a loudspeaker located some distance above the road surface does not create a wave that is plane enough for porous road surfaces.

3.3 CORRECTIONS FROM SPHERICAL TO PLANE WAVES

Some relevant corrections must be calculated and added to the measured sound absorption coefficient. It is fairly straight forward to set up accurate corrections for cases where the porous road thickness is small compared to a fraction of the wavelength (i.e. where only one sound reflecting surface must be considered) and the sound absorption coefficient approaches 1 (great value of flow resistance) at higher frequencies. In other cases (i.e. where two sound reflecting surfaces must be considered) the corrections will be very complicated or iterative. For most porous roads, two sound reflecting surfaces must be considered.

3.4 ALTERNATIVES TO CORRECTIONS

An alternative strategy, instead of using corrections, might be to create almost plane waves by shaping the sound field radiated from the loudspeaker(s). That can be done in at least two different ways:

1) One loudspeaker combined with a parabolic reflector or
2) A number of loudspeakers densely mounted in a closed box.

3.5 PARABOLIC REFLECTOR

In figure 5 is illustrated a system arrangement with a parabolic reflector and a single microphone.

If just a single microphone is used /1/ (intensity method), then the loudspeaker must generate transient sound regardless of the selected loudspeaker alternative, as the direct sound pressure hitting the microphone must be separated from the delayed and reflected sound pressure.

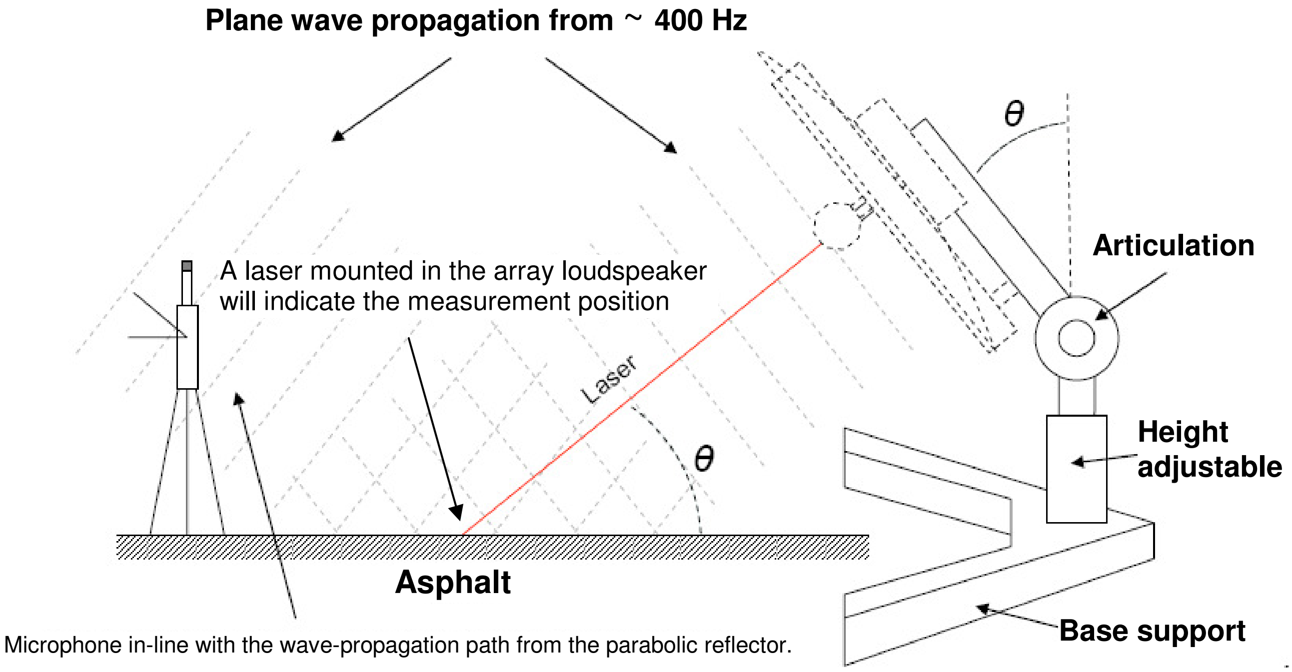


Figure 5 *Measurement set-up with a* ***parabolic reflector*** *and one microphone. Gated technique in time-domain need to be employed.*

3.6 LOUDSPEAKER ARRAY

In figure 6 is illustrated a measurement system with a loudspeaker array and two microphones (PU-probe).

If two microphones are used (wave impedance method), then the loudspeaker(s) might generate stationary sound regardless of the selected loudspeaker alternative, as the direct particle velocity hitting the microphones can be separated from the reflected particle velocity.

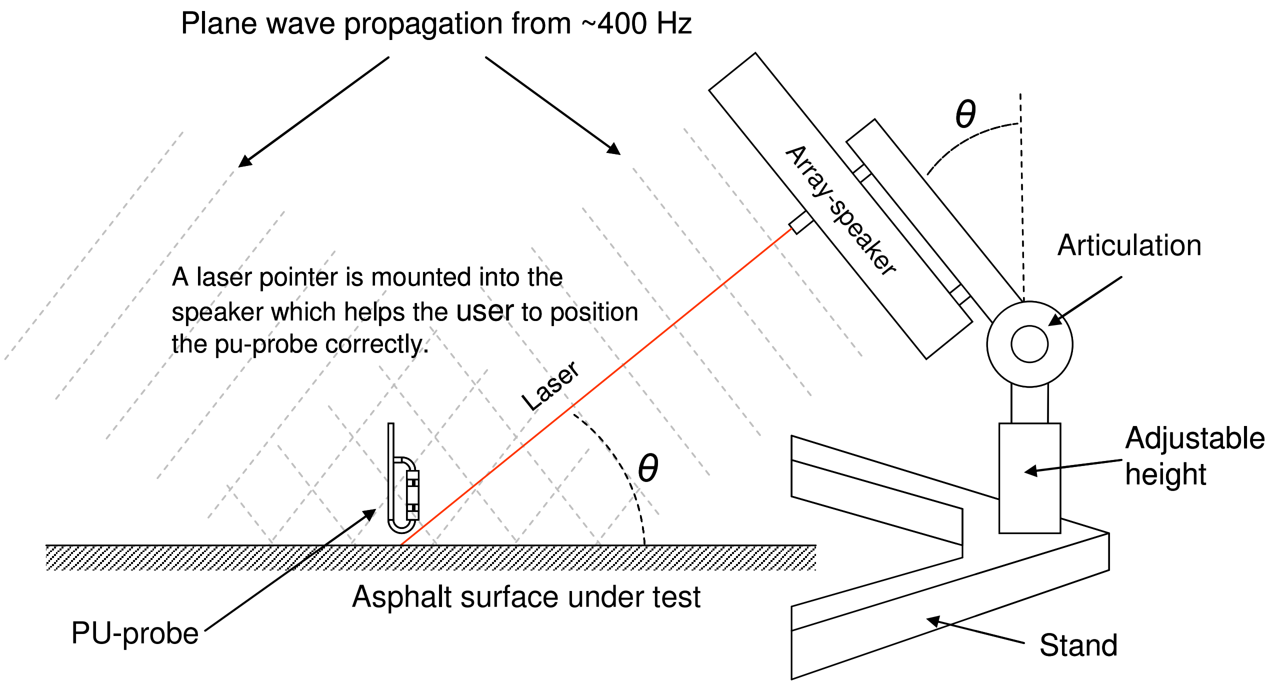
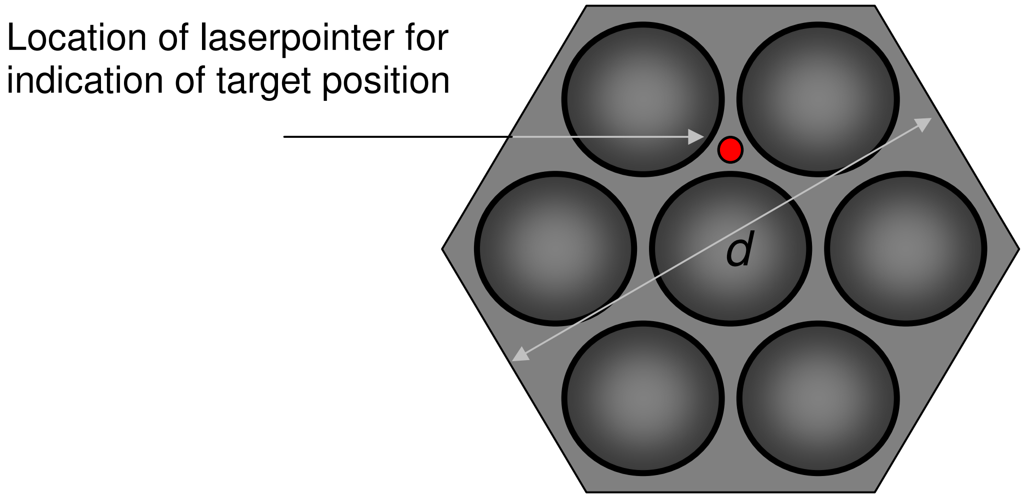


Figure 6 *Measurement set-up with a* ***loudspeaker array*** *and a* *<u>two</u>-microphone-probe*



Speaker-array

$d = \lambda_{\max}$

Figure 7 *Arrangement of seven loudspeakers in a loudspeaker array*

3.7 LIMITATIONS

All field methods discussed so far have limitations at lower frequencies (much less for Kundt's tube), where the expected sound absorption coefficient is very small and thus the direct and reflected pressures and/or particle velocities are almost equal. The diameters of the parabolic reflector and loudspeaker array are also causing limitations at lower frequencies.

Therefore, it is suggested that the sound absorption coefficient at lower frequencies will be determined by an interpolation procedure based on a fairly simple mathematical function between zero and the lowest frequency, where the accuracy of the measured sound absorption coefficient is sufficient.

The accuracy of the laboratory method based on Kundt's tube is probably very good within a specific frequency range around the $\lambda/4$-resoanance and less good outside that range. Probably, the magnitude of this error is acceptable.

The expected frequency ripple on the sound absorption coefficient for plane waves at oblique incidence is neglected in the calculations (straight **blue** line in figure 4). That might result in a somewhat lower calculated average absorption coefficient than expected in particular close to normal incidence. However, this error is probably rather small for a typical oblique incidence around 45 degrees.

4 CONCLUSIONS

A method has been developed to determine the sound absorption coefficient for oblique incidence of plane waves against porous road surfaces. This method is based on absorption measurements in Kundt's tube on porous road samples and a set of equations and so far the method seems to be reliable. Besides, a dimensionless simple sound absorption **Index** has been created for ranking and optimization of porous road samples. This **Index** is based on selected quantities resulting from the mentioned equations.

However, this method is based on laboratory road samples in Kundt's tube, which might be cut out of real road surfaces or just manufactured for laboratory tests. Thus, the method can not be used for corresponding direct field measurements of the sound absorption coefficient for oblique incidence.

In many cases it might be preferred to make direct field measurements of the sound absorption coefficient for oblique incidence. It would e.g. be an advantage because it would provide possibilities to perform a non-destructive testing of sound absorption at the current road section under evaluation. That is why we have investigated, evaluated and presented methods and measurement devices for such field measurements (see ch 3).

5 REFERENCES

/1/ ISO 13472-1:2002(E).
Acoustics – Measurement of sound absorption properties of road surfaces *in situ*. Part 1: Extended surface method.