STUDY OF THE ACOUSTIC PERFORMANCES OF PAVEMENTS MADE OF BITUMINOUS MIXTURES

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Synopsis

In the following paper the Authors present the results of a study based on the comparative evaluation of the sound absorption characteristics of bituminous mixtures with different compositions. The results have been obtained by determining experimentally the values of sound absorption coefficients α of the mixtures.
Draining mixtures, draining mixtures with fibres in pure cellulose, double draining layer mixtures and antiskid mixtures have been manufactured to be subjected to the Kundt's tube standard method.
This study shows the contribution that a binder course placed under the friction layer can give to sound absorption.
All the samples have been subjected with various frequencies from 400 to 1800 Hz.
The results of this study prove the substantial equivalence of sound absorption characteristics between draining mixtures and draining mixtures with fibres; also double draining layer mixtures and antiskid mixtures have provided good performances.
Moreover, the contribution of the layers used under the friction layer appears very important in relation to sound absorption.
The methodology used has revealed itself suitable for comparative measurements of sound absorption in mixtures of different materials and compositions used to make friction layers.
The measurement protocol applied to the experimentation, based on a statistical survey, allows finding possible errors made during the measurement or manufacture of the samples by who operates.

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INTRODUCTION

The main characteristic of a modern pavement is to guarantee traffic safety and comfort with total respect for the environment.
The study of the impact of road infrastructures on the environment is very important in consideration of traffic noise and noise pollution which are known for being the main causes of the decline in quality of life especially within the cities.
Noise limits have been imposed by the law to reduce the negative effects of this phenomenon [1].
Moreover, many local governments have regulated the acoustic behaviour of the most common pavements in the *Capitolati Speciali d'Appalto* [2, 3].
On the other hand, the population increment on the territory has increased the demand for transport of goods by road which causes a considerable environmental impact due to air and acoustic pollution.
Experts in this field have tested porous bituminous mixtures with draining properties and good sound absorption capabilities to reduce the noise caused by traffic.
Noise is the effect of the emission of vibrations from an acoustic source; the vibrations are transmitted to a means which propagates them as pressure variations called acoustic waves or sound [4].
Traffic noise depends on the type of vehicle and on the context in which it is produced.
In extra-urban areas, where speed limits are generally higher than 50 Km/h., the principal source of noise made by vehicles (cars and heavy vehicles) is the contact between the tyres and the pavement, whereas the noise made by the engine and the gas release systems can be ignored.
Moreover, the rolling noise depends on different factors [5], as air-pumping, due to the air constrained in the dihedral formed by the road and tyre surfaces; this phenomenon produces acoustic energy which is reflected by the pavement.
In urban areas, where speed limits are generally low for vehicles, whereas motorcycles have different noise mechanisms, the engine and the gas release systems are the principal source of traffic noise.
The sound absorption capabilities of pavements are able to reduce rolling noise.
Pavements with high porosity reduce the air-pumping effect by absorbing the acoustic energy because the air between tyre and pavements is able to move through the air voids, whereas dense pavements tend to reflect that energy.
The purpose of this research is to compare the acoustic performances of pavements made of bituminous mixtures.
The Authors have compared the characteristics and the performances of the materials used in friction layers [6], by subjecting the bituminous mixtures [7, 8] to the Kundt's tube test to evaluate for each mixture the sound absorption α of the normal incident waves.

PRELIMINARY STUDY

The experiment is based on the analysis of the acoustic performances therefore it considers the measures of the sound absorption coefficients α_i of 5 samples of different mixtures used in 5 cm thick friction layers, compacted by using the Marshall method, which are:

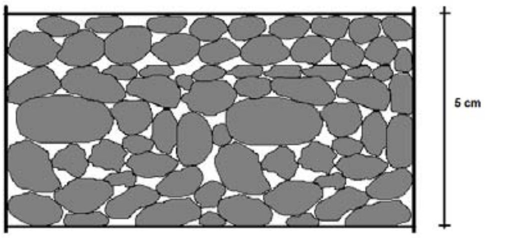
- Draining mixtures (D.M.);
- Draining mixtures with fibres in pure cellulose (D.M.F.);
- Double draining layer mixtures (D.D.L.M.)
- Antiskid mixtures (A.M.);

Considering that this is a comparative evaluation, not an absolute evaluation, it seems suitable to calculate the coefficient α for normal incident waves, although this coefficient does not consider the reflection angle of acoustic waves.
During the experimentation 5 cm thick binder courses have been placed under the friction layers of all the mixtures to test the contribution that the binder courses may give to the sound absorption; the samples have been indicated as follows:

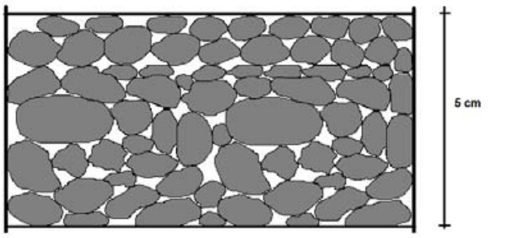
- Draining pavements (D.P.);

- Draining pavements with fibres (D.P.F.);
- Double draining layer pavements (D.D.L.P.);
- Antiskid pavements (A.P.);

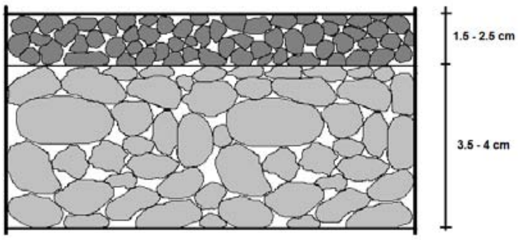
All the samples have been subjected to various frequencies from 400 to 1800 Hz, in accordance with the *Capitolati Speciali d'Appalto*.
Moreover, the mixtures have been subjected to mechanical tests, as the Marshall test and the indirect tension strength test.
The mixtures with and without binder courses used for the experiment are the following:



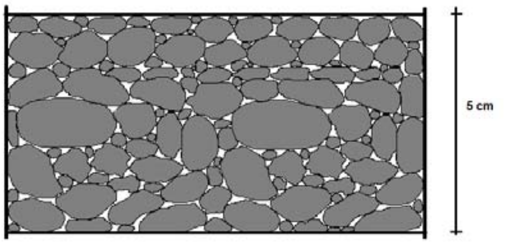
Draining mixture (D.M.)



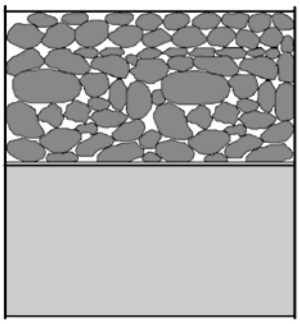
Draining mixture with fibres in pure cellulose (D.M.F.)



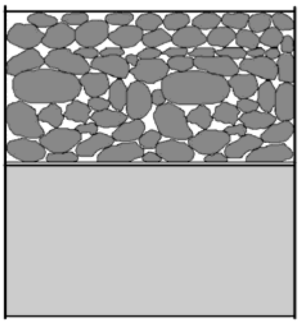
Double draining layer mixture (D.D.L.M.)



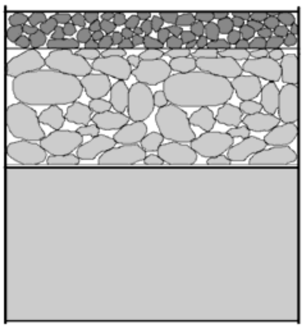
Antiskid mixture (A.M.)



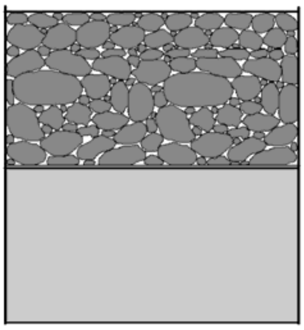
Draining pavement (D.P.)



Draining pavement with fibres (D.P.F.)



Double draining layer pavement (D.D.L.P.)



Antiskid pavement (A.P.)

CHARACTERISTICS OF MIXTURES TESTED WITH KUNDT'S TUBE

Draining bituminous mixture

The draining bituminous mixture used in the experiment is made of calcareous sand, basaltic grit, basaltic fine-crushed aggregates and of a percentage of 5.3% of 50/70 bitumen modified with thermoplastic elastomeric polymers.
The granulometric composition of the mixture is written in the following table:

GRANULOMETRIC ANALYSIS														
Aggregate type	SAND				GRIT				FINE CRUSHED AGGREGATE					
DRAINING BITUMINOUS MIXTURES														
Aggregate weight	598,46 g				1857 g				2298 g					
Sieve diameter (mm)	Cumulative not passing	% Not passing	% Passing	% 16	Cumulative not passing	% Not passing	% Passing	% 32	Cumulative not passing	% Not passing	% Passing	% 52	TOTAL PASSING
40	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
30	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
25	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
20	0,00	0,0	**100,0**	16,0	0,00	0,0	**100,0**	32,0	0,00	0,0	**100,0**	52,0	100,0
15	0,00	0,0	**100,0**	16,0	3,04	0,2	**99,8**	31,9	874,00	38,0	**62,0**	32,2	80,2
10	0,00	0,0	**100,0**	16,0	777,04	41,8	**58,2**	18,6	2281,00	99,3	**0,7**	0,4	35,0
5	15,41	2,6	**97,4**	15,6	1843,04	99,2	**0,8**	0,2	2290,36	99,7	**0,3**	0,2	16,0
2	206,86	34,6	**65,4**	10,5	1849,15	99,6	**0,4**	0,1	2290,50	99,7	**0,3**	0,2	10,8
1	366,92	61,3	**38,7**	6,2	1849,49	99,6	**0,4**	0,1	2290,56	99,7	**0,3**	0,2	6,5
0,425	466,40	77,9	**22,1**	3,5	1849,66	99,6	**0,4**	0,1	2290,64	99,7	**0,3**	0,2	3,8
0,18	516,68	86,3	**13,7**	2,2	1849,83	99,6	**0,4**	0,1	2290,79	99,7	**0,3**	0,2	2,5
0,075	536,03	89,6	**10,4**	1,7	1850,39	99,6	**0,4**	0,1	2293,32	99,8	**0,2**	0,1	1,9

The characteristics of the 5 samples that have been subjected to the Kundt's tube test are the following:
Mean apparent volumic mass [9]: 2.01 gr/cm^3; Mean porosity [10]: 20%

Draining bituminous mixtures with addition of fibres

Fibres of pure cellulose compressed in granules, produced by Iterfibra/C, have been added in the amount of 0.4% of the aggregate's weight, to the same mixture seen in the previous paragraph.
The fibres have been preventively crushed and carefully mixed with the aggregates, and then the bitumen has been added.
The characteristics of the 5 samples that have been subjected to the Kundt's tube test are the following:
Mean apparent volumic mass: 2.02 gr/cm^3; Mean porosity: 21%.

Double draining layer bituminous mixture

Top layer

The bituminous mixture of the higher layer has been made by using calcareous sand, Portland cement, basaltic grit, dolomite grit and of a percentage of 5.3% of 50/70 bitumen modified with thermoplastic elastomeric polymers.
The granulometric composition of the mixture is written in the following table:

GRANULOMETRIC ANALYSIS																	
Aggregate type		SAND (calcareus)			GRIT 1 (basalt)				GRIT 2 (dolomite)				CEMENT				
Aggregate weight		611,71 g			1857 g				1815,4 g				500 g				
D.D.L. MIXTURE – TOP LAYER																	
Sieve diam. (mm)	Cum. not passing	% Not passing	% Passing	% 10	Cumulative not passing	% Not passing	% Passing	% 37	Cumulative not passing	% Not passing	% Passing	% 50	Cumulative not passing	% Not passing	% Passing	% 3	Tot pas
20	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	37,0	0,00	0,0	**100,0**	50,0	0,00	0,0	**100,0**	3,0	**100**
15	0,00	0,0	**100,0**	10,0	3,04	0,2	**99,8**	36,9	0,00	0,0	**100,0**	50,0	0,00	0,0	**100,0**	3,0	**100**
10	0,00	0,0	**100,0**	10,0	777,04	41,8	**58,2**	21,5	0,00	0,0	**100,0**	50,0	0,00	0,0	**100,0**	3,0	**85**
5	34,86	5,7	**94,3**	9,4	1843,04	99,2	**0,8**	0,3	1541,30	84,9	**15,1**	7,5	0,00	0,0	**100,0**	3,0	**20**
2	215,67	35,3	**64,7**	6,5	1849,15	99,6	**0,4**	0,2	1737,70	95,7	**4,3**	2,1	0,00	0,0	**100,0**	3,0	**12**
0,425	431,59	70,6	**29,4**	2,9	1849,66	99,6	**0,4**	0,1	1779,60	98,0	**2,0**	1,0	0,00	0,0	**100,0**	3,0	**7**
0,18	486,49	79,5	**20,5**	2,0	1849,83	99,6	**0,4**	0,1	1784,80	98,3	**1,7**	0,8	0,50	0,1	**99,9**	3,0	**6**
0,075	517,34	84,6	**15,4**	1,5	1850,39	99,6	**0,4**	0,1	1790,20	98,6	**1,4**	0,7	18,20	3,6	**96,4**	2,9	**5**

The characteristics of the 5 samples that have been subjected to the Kundt's tube test are the following:
Mean apparent volumic mass [9]: 2.10 gr/cm^3; Mean porosity [10]: 17%.

Bottom layer

The bituminous mixture of the bottom layer has been made by using sand, grit, fine-crushed calcareous aggregates and 50/70 bitumen modified with 5.3% of thermoplastic elastomeric polymers.
The granulometric composition of the mixture is written in the following table:

GRANULOMETRIC ANALYSIS													
Aggregate type		**SAND**			**GRIT** (calcareous)				**FINE CRUSHED AGGREGATE** (calcareous)				
Aggregate weight		611,71 g			1956 g				1930 g				
D.D.L. MIXTURE – BOTTOM LAYER													
Sieve diam. (mm)	Cumulative not passing	% Not passing	% Passing	% 10	Cumulative not passing	% Not passing	% Passing	% 21	Cumulative not passing	% Not passing	% Passing	% 69	TOT Pass.
40	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	21,0	0,00	0,0	**100,0**	69,0	**100,0**
30	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	21,0	0,00	0,0	**100,0**	69,0	**100,0**
25	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	21,0	0,00	0,0	**100,0**	69,0	**100,0**
20	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	21,0	42,49	2,2	**97,8**	67,5	**98,5**
15	0,00	0,0	**100,0**	10,0	3,04	0,2	**99,8**	21,0	550,33	28,5	**71,5**	49,3	**80,3**
10	0,00	0,0	**100,0**	10,0	35,71	1,8	**98,2**	20,6	1830,49	94,8	**5,2**	3,6	**34,2**
5	34,86	5,7	**94,3**	9,4	1788,71	91,4	**8,6**	1,8	1918,49	99,4	**0,6**	0,4	**11,6**
2	215,67	35,3	**64,7**	6,5	1889,71	96,6	**3,4**	0,7	1918,71	99,4	**0,6**	0,4	**7,6**
1	343,02	56,1	**43,9**	4,4	1902,11	97,2	**2,8**	0,6	1918,89	99,4	**0,6**	0,4	**5,4**
0,425	431,59	70,6	**29,4**	2,9	1904,79	97,4	**2,6**	0,5	1919,04	99,4	**0,6**	0,4	**3,9**
0,18	486,49	79,5	**20,5**	2,0	1911,09	97,7	**2,3**	0,5	1919,27	99,4	**0,6**	0,4	**2,9**
0,075	517,34	84,6	**15,4**	1,5	1932,19	98,8	**1,2**	0,3	1919,77	99,5	**0,5**	0,4	**2,2**

The characteristics of the 5 samples that have been subjected to the Kundt's tube test are the following:
Mean apparent volumic mass [9]: 2.01 gr/cm^3; Mean porosity [10]: 19%.

Double layer system

Considering a double draining layer mixture as one double layer system, in which the higher layer is 2 cm thick and the bottom layer is 3 cm thick, the mean apparent volumic mass and the mean percentage porosity of the whole system can be determined by making the weighted average between the values obtained for each layer, that is:

$$\gamma_{DSD} = \frac{\sum_{k=1}^{2} \gamma_k \cdot p_k}{\sum_{k=1}^{2} p_k}$$

from which the following result is found $\gamma_{DDL} = 2.05$ g/cm^3.
Mean porosity: 18.2%.

Antiskid bituminous mixture

The antiskid bituminous mixture has been made by using calcareous sand, basltic grit, dolomite grit and of a percentage of 5.3% of 50/70 bitumen modified with thermoplastic elastomeric polymers.
The granulometric composition of the mixture is written in the following table:

GRANULOMETRIC ANALYSIS

Aggregate type	**SAND** (calcareous)				**GRIT 1** (basalt)				**GRIT 2** (calcareous dolomite)				
Aggregate weight	611,71 g				1857 g				1815,4 g				
ANTISKID MIXTURE													
Sieve diameter (mm)	Cumulative not passing	% Not passing	% passing	% 42	Cumulative not passing	% Not passing	% passing	% 30	Cumulative not passing	% Not passing	% passing	% 28	TOTAL Passing
20	0,00	0,0	**100,0**	42,0	0,00	0,0	**100,0**	30,0	0,00	0,0	**100,0**	28,0	**100,0**
15	0,00	0,0	**100,0**	42,0	3,04	0,2	**99,8**	30,0	0,00	0,0	**100,0**	28,0	**100,0**
10	0,00	0,0	**100,0**	42,0	777,04	41,8	**58,2**	17,4	0,00	0,0	**100,0**	28,0	**87,4**
5	34,86	5,7	**94,3**	39,6	1843,04	99,2	**0,8**	0,2	1541,30	84,9	**15,1**	4,2	**44,1**
2	215,67	35,3	**64,7**	27,2	1849,15	99,6	**0,4**	0,1	1737,70	95,7	**4,3**	1,2	**28,5**
0,425	431,59	70,6	**29,4**	12,4	1849,66	99,6	**0,4**	0,1	1779,60	98,0	**2,0**	0,6	**13,0**
0,18	486,49	79,5	**20,5**	8,6	1849,83	99,6	**0,4**	0,1	1784,80	98,3	**1,7**	0,5	**9,2**
0,075	517,34	84,6	**15,4**	6,5	1850,39	99,6	**0,4**	0,1	1790,20	98,6	**1,4**	0,4	**7,0**

The characteristics of the 5 samples that have been subjected to the Kundt's tube test are the following:
Mean apparent volumic mass [11]: 2.32 gr/cm^3; Mean porosity [12]: 6.8 %.

Binder course

The binder course has been made by using calcareous sand, basltic grit, fine-crushed basaltic aggregates and of a percentage of 5.3% of 50/70 bitumen modified with thermoplastic elastomeric polymers.
The granulometric composition of the mixture is written in the following table:

GRANULOMETRIC ANALYSIS													
Aggregate type	SAND				BASALTIC GRIT				BASALTIC FINE CRUSHED AGGREGATE				
Aggregate weight	598,46 g				1857 g				2298 g				
BINDER													
Sieve diameter (mm)	Cumulative not passing	% Not passing	% Passing	% 55	Cumulative not passing	% Not passing	% Passing	% 10	Cumulative not passing	% Not passing	% Passing	% 35	TOT Pass
25	0,00	0,0	**100,0**	55,0	0,00	0,0	**100,0**	10,0	0,00	0,0	**100,0**	35,0	**100,0**
15	0,00	0,0	**100,0**	55,0	3,04	0,2	**99,8**	10,0	874,00	38,0	**62,0**	21,7	**86,7**
10	0,00	0,0	**100,0**	55,0	777,04	41,8	**58,2**	5,8	2281,00	99,3	**0,7**	0,3	**61,1**
5	15,41	2,6	**97,4**	53,6	1843,04	99,2	**0,8**	0,1	2290,36	99,7	**0,3**	0,1	**53,8**
2	206,86	34,6	**65,4**	36,0	1849,15	99,6	**0,4**	0,0	2290,50	99,7	**0,3**	0,1	**36,1**
0,425	466,40	77,9	**22,1**	12,1	1849,66	99,6	**0,4**	0,0	2290,64	99,7	**0,3**	0,1	**12,3**
0,18	516,68	86,3	**13,7**	7,5	1849,83	99,6	**0,4**	0,0	2290,79	99,7	**0,3**	0,1	**7,7**
0,075	536,03	89,6	**10,4**	5,7	1850,39	99,6	**0,4**	0,0	2293,32	99,8	**0,2**	0,1	**5,8**

MEASURMENT METHODOLOGY OF THE ABSORPTION COEFFICIENT

The Kundt's tube method has been used to measure the absorption coefficients, in accordance with the UNI EN ISO 10534/2001 [13]. In Fig. 1 there is a photograph of the experimental system supplied with a Kundt's tube produced by the Danish Company Bruel & Kjaer.

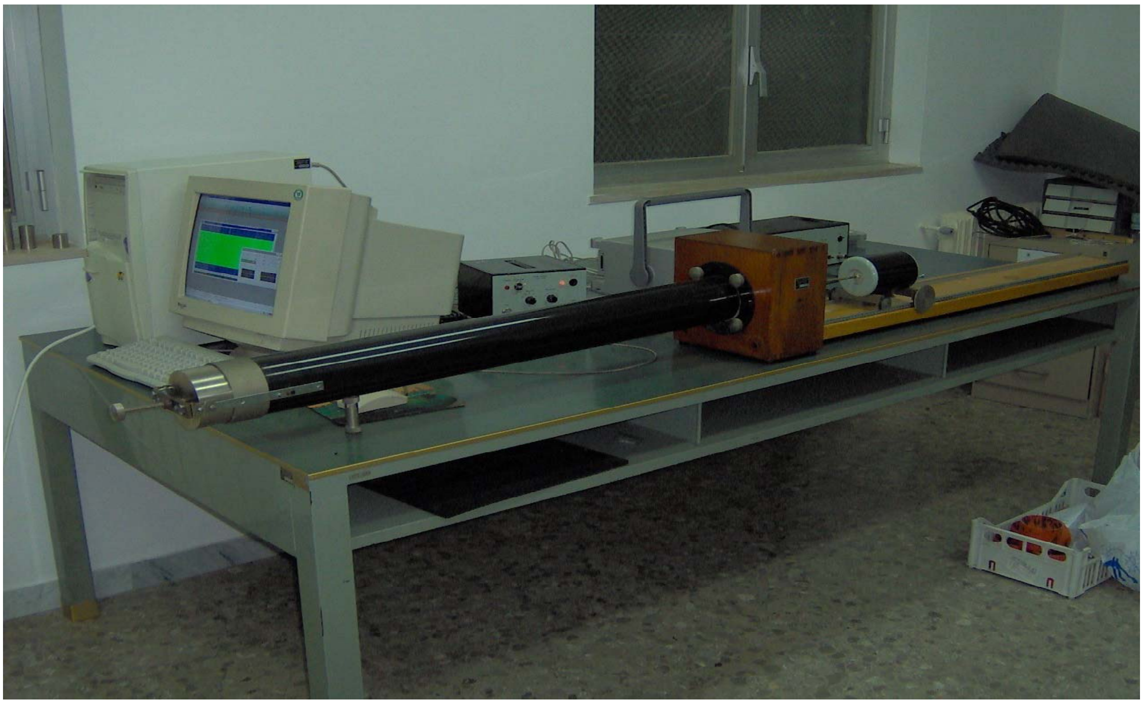


Fig. 1- Photograph of the experimental system used for the absorption coefficient measurement

The system consists of a tube with a diameter reduced to allow only the propagation of plane waves the requested frequency field; at one end of the tube there is a loudspeaker, while at the other end there is the sample, whose absorption coefficient is measured (Fig. 2).

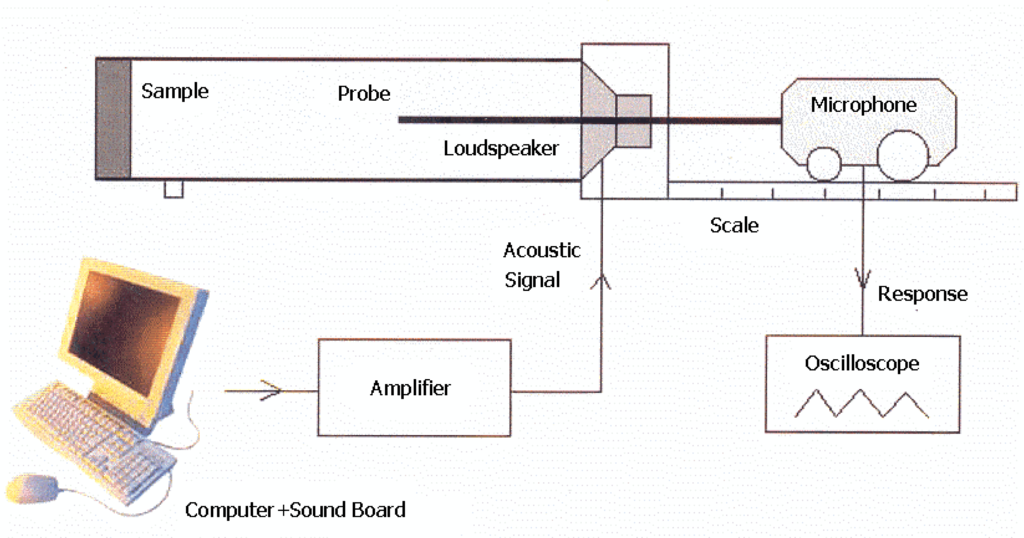


Fig. 2 – Diagram of the measurement system based on the Kundt's tube.

The loudspeaker produces in the tube a simple tone with pressure amplitude indicated by P_{inc} and with the chosen frequency; in this kind of experiment the tones are generated by a 16 bit sound board and by a computer sampling frequency of 44.1 kHz and then they are amplified by a Bruel & Kjaer mod. 2704 amplifier.
When the sound affects the sample, part of the acoustic energy is absorbed and part is reflected backwards producing a pressure wave with lower pressure amplitude P_{ref}. Consequently, the destructive interference produced in the tube between the incident wave and the reflected wave generates a partially standing acoustic field.
If the sample is perfectly reflective, the reflected wave presents the same amplitude of the incident wave, but in a totally opposite phase, so that a field of completely standing waves due to the destructive interference between the incident and the reflected wave is generated in the tube.
Consequently, the generated wave presents *nodes* in which pressure is null and antinodes in which the pressure has double amplitude than the pressure of the incident wave (Fig. 3).

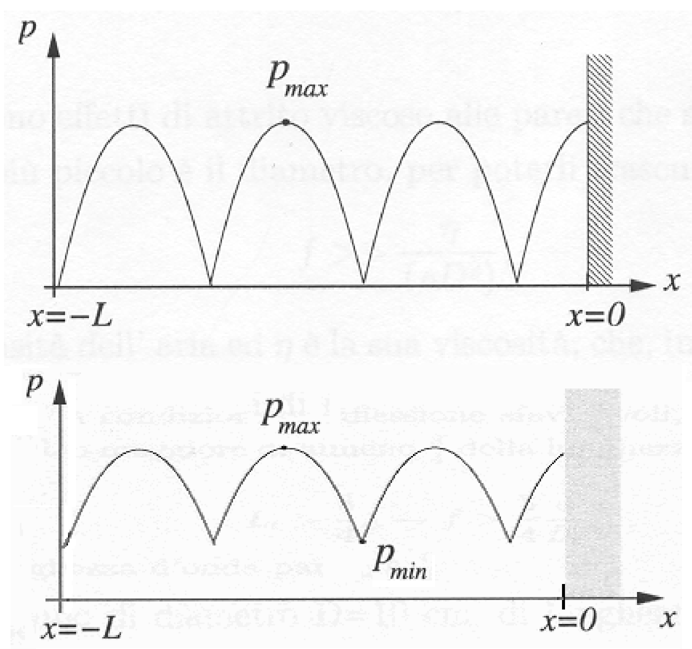


Fig. 3 – Pressure field produced by a non absorbent sample (above) and by an absorbent sample (below).

If the sample has absorbent properties, the amplitude of the reflected wave is lower therefore the destructive interference in the nodes is not complete so the acoustic field presents minimum points which are not null. Therefore, measuring the pressure in the minimum and maximum points by using a microphone and an oscilloscope, that is able to visualize the temporal trend of the signal captured by the microphone, the absorption coefficient value can be easily deduced. In particular, the absorption coefficient value can be expressed as a function of the Standing Wave Ratio, which is the ratio between the maximum pressure P_{max} and the minimum pressure P_{min} values [14].
In fact, in acoustics the absorption coefficient is related to the reflection coefficient as follows:

$$\alpha = 1 - r$$

where the reflection coefficient *r* is the reflected fraction of the energy that affects the sample. The acoustic intensity of a plane wave can be expressed as a function of the acoustic pressure of the wave:

$$I_{inc} = \frac{1}{2}\frac{P_{inc}^{\ 2}}{\rho_o c} \qquad I_{rif} = \frac{1}{2}\frac{P_{rif}^{\ 2}}{\rho_o c}$$

consequently:

$$\alpha = 1 - \frac{P_{rif}^{\ 2}}{P_{inc}^{\ 2}}$$

The ratio between the pressures can be expressed as a function of the Standing Wave Ratio considering that the maximum and minimum pressure in the tube are respectively equal to the sum and the difference between the amplitude of the incident and reflected waves:

$$P_{\max} = P_{inc} + P_{rif}$$

$$P_{\min} = P_{inc} - P_{rif}$$

from which the Standing Wave Ratio is obtained:

$$SWR = \frac{P_{\max}}{P_{\min}} = \frac{P_{inc} + P_{rif}}{P_{inc} - P_{rif}}$$

and then:

$$\frac{P_{rif}}{P_{inc}} = \frac{SWR - 1}{SWR + 1}$$

Finally, the absorption coefficient is:

$$\alpha = 1 - \frac{P_{rif}^{\ 2}}{P_{inc}^{\ 2}} = 1 - \left(\frac{SWR - 1}{SWR + 1}\right)^2$$

Determining the value of the Standing Wave Ratio by measuring the pressure in the minimum and maximum points, the absorption coefficient value of the sample can be easily calculated.
The diameter of the tube must be smaller than the wave length of sound [15], because the system is based on a plane wave field.

The experiment has been carried out by using a tube with a 10 cm diameter, which is able to measure up to 1800 Hz; anyway, the frequency field cannot be extended by using a tube with a smaller diameter because the samples are not sufficiently homogeneous.

MEASURMENT PROTOCOL

The experiment has been carried out in the Laboratory of Acoustics of the Department of Applied Physics in the *Politecnico di Bari*.
The criterion used considers the particular composition of the samples, which are not homogeneous neither isotropic, because of the high percentage of air voids in the bituminous mixtures.
Moreover, other dishomogeneities between samples of the same mixture can be produced during the mixing and compacting phases, although using the same procedure and the same materials.
For this reason it's possible to find different absorption coefficients α_1 for samples of the same mixture at the same frequencies.
Therefore, five samples of each type of mixture to which the binder course has been added have been manufactured: each sample with and without binder courses has been subjected to frequencies of 400, 500, 630, 800, 1250, 1600 and 1800 Hz.
The absorption coefficient values α_1 have been surveyed at each frequency and for each sample.
The measurements of each sample with and without binder courses have been repeated at least three times to reduce possible errors therefore obtaining a root mean square deviation lower than 10-15% in 3 measurements.
The experimental results of the different mixtures are written in different tables, in which the standard deviation (or root mean square deviation) of the 3 measures and their percentage value have been written for each sample.
The value of the absorption coefficient of each sample has been then assumed equal to the mean value of the 3 measures.
In order to verify the credibility and the repeatability of the results obtained, the same procedure has been repeated for all the five samples (for two in the draining friction layer-binder course system) and at all frequencies, 588 measurements in total.
The congruity test of the measures allows finding possible errors in the absorption coefficients measurement of each sample and in the manufacture of the samples.
The experimental data reveal that the absorption coefficient of the 5 samples made of the same mixture a arrange themselves around a mean value with a limited scattering of data, so that it has been possible to assign to each mixture an absorption coefficient calculated as the mean value of the 5 samples.
Whether the sample had an absorption coefficient significantly different from the others it would have been suitable not considering it in the calculation of the mean value.

Experimental results

Here are the experimental results of all the mixtures that have been tested. In order to verify the contribution to sound absorption of the layers placed under the friction layer, the binder course has been added to two samples of each mixture.
Also these samples indicated by "pavement" have been subjected to the Kundt's tube method.
Only the experimental results of the five samples of the draining mixture and of all their frequencies are written in detail in the following table.
For all the mixtures with and without the presence of the binder course, the experimental results will be synthetically written in the diagram titled Frequencies – Absorption coefficients.

Draining mixture (D.M.)

DETERMINATION OF SOUND ABSORPTION COEFFICIENT KUNDT'S TUBE- DRAINING FRICTION LAYER-- frequencies 400 – 500 – 630 (Hz)											
Sample	FREQUENCY (Hz)		**400**	Sample	FREQUENCY (Hz)		**500**	Sample	FREQUENCY (Hz)		**630**
N°	Vp-p	Vavg	**Alfa**	N°	Vp-p	Vavg	**Alfa**	N°	Vp-p	Vavg	**Alfa**
1	15,62	2,75	0,12	**1**	6,25	1,28	0,37	**1**	4,68	1,70	0,41
	500,00	3,57			54,89	1,75			35,90	1,92	
	15,62	2,68	0,12		6,25	1,20	0,37		4,66	1,75	0,47
	478,10	3,78			54,69	1,75			29,69	1,99	
	15,62	2,81	0,13		7,80	1,20	0,44		6,25	1,45	0,56
	437,50	3,74			54,69	1,83			31,25	1,92	
Standard deviation			0,0065	**Standard deviation**			0,0327	**Standard deviation**			0,0605
Deviation %			5,2	**Deviation %**			8,4	**Deviation %**			12,7
Mean alfa			**0,12**	**Mean alfa**			**0,39**	**Mean alfa**			**0,48**
2	12,50	2,87	0,10	**2**	15,62	2,71	0,51	**2**	6,25	2,94	0,40
	462,50	3,65			87,50	3,41			50,00	3,25	
	15,62	2,69	0,13		15,62	2,58	0,51		6,25	3,25	0,40
	453,10	3,57			87,50	3,57			50,00	3,40	
	15,62	2,56	0,13		12,50	2,64	0,44		6,25	3,15	0,40
	459,40	3,69			87,50	3,46			50,00	3,27	
Standard deviation			0,0121	**Standard deviation**			0,0361	**Standard deviation**			0,0000
Deviation %			10,1	**Deviation %**			7,4	**Deviation %**			0,0
Mean alfa			**0,12**	**Mean alfa**			**0,49**	**Mean alfa**			**0,40**
3	15,62	2,81	0,13	**3**	7,81	1,50	0,40	**3**	6,25	3,03	0,40
	456,20	3,58			60,94	1,80			50,00	3,33	
	15,62	2,55	0,13		6,25	1,70	0,35		6,25	3,22	0,38
	462,50	3,64			57,81	1,92			53,12	3,34	
	15,62	2,95	0,13		7,81	1,60	0,44		6,25	3,07	0,40
	456,20	3,64			54,69	1,90			50,00	3,35	
Standard deviation			0,0008	**Standard deviation**			0,0350	**Standard deviation**			0,0086
Deviation %			0,6	**Deviation %**			8,8	**Deviation %**			2,2
Mean alfa			**0,13**	**Mean alfa**			**0,40**	**Mean alfa**			**0,39**
4	18,75	2,41	0,15	**4**	6,25	1,40	0,34	**4**	6,25	2,88	0,40
	456,20	3,75			60,94	1,91			50,00	3,32	
	18,75	2,41	0,16		7,81	1,30	0,44		6,25	2,98	0,40
	434,40	3,73			54,69	1,90			50,00	3,37	
	18,75	2,57	0,16		7,81	1,20	0,43		6,25	2,37	0,40
	431,20	3,73			56,25	2,00			50,00	3,37	
Standard deviation			0,0036	**Standard deviation**			0,0451	**Standard deviation**			0,0000
Deviation %			2,3	**Deviation %**			11,2	**Deviation %**			0,0
Mean alfa			**0,16**	**Mean alfa**			**0,40**	**Mean alfa**			**0,40**
5	10,94	1,40	0,13	**5**	15,62	2,51	0,54	**5**	6,25	1,36	0,50

	310,5	2,32			81,25	3,41			35,94	1,98	
	8,25	1,18	0,10		15,62	2,54	0,49		6,25	1,55	0,49
	306,2	2,23			93,75	3,43			37,5	1,83	
	9,37	1,72	0,11		15,62	2,41	0,51		7,81	1,29	0,53
	326,6	2,31			87,5	3,35			42,19	1,91	
Standard deviation			0,0126	**Standard deviation**			0,0210	**Standard deviation**			0,0154
Deviation %			11,1	**Deviation %**			4,1	**Deviation %**			3,0
Mean alfa			**0,11**	**Mean alfa**			**0,51**	**Mean alfa**			**0,51**
Mean alfa of 5 samples			**0,13**	**Mean alfa of 5 sample**			**0,44**	**Mean alfa of 5 sample**			**0,43**
Standard deviation of 5 samples			0,0148	**Standard deviation of 5 samples**			0,0524	**Standard deviation of 5 samples**			0,0496
Deviation % of 5 samples			11,6	**Deviation % of 5 samples**			11,9	**Deviation % of 5 samples**			11,5

DETERMINATION OF SOUND ABSORPTION COEFFICIENT
KUNDT'S TUBE- DRAINING FRICTION LAYER—frequencies 800 – 1250 – 1600 (Hz)

Sample N°	FREQUENCY (Hz)		800	Sample N°	FREQUENCY (Hz)		1250	Sample N°	FREQUENCY (Hz)		1600
	Vp-p	Vavg	Alfa		Vp-p	Vavg	Alfa		Vp-p	Vavg	Alfa
1	14,06	1,65	0,65	**1**	15,62	2,80	0,57	**1**	4,68	1,87	0,75
	54,69	1,93			75,00	3,27			14,06	2,28	
	18,75	1,80	0,83		18,75	2,97	0,69		7,80	1,30	0,92
	45,31	1,97			65,62	3,51			14,06	2,00	
	18,75	1,68	0,78		18,75	2,83	0,61		7,80	1,50	0,92
	51,56	1,89			81,25	3,20			14,06	2,40	
Standard deviation			0,0752	**Standard deviation**			0,0503	**Standard deviation**			0,0794
Deviation %			9,6	**Deviation %**			8,3	**Deviation %**			8,7
Mean alfa			**0,75**	**Mean alfa**			**0,62**	**Mean alfa**			**0,86**
2	31,25	3,25	0,75	**2**	18,75	3,22	0,60	**2**	4,68	1,87	0,75
	93,75	3,51			84,38	3,43			14,06	2,20	
	31,25	3,19	0,73		18,75	2,82	0,64		6,25	1,70	0,85
	100,00	3,42			75,00	3,25			14,06	2,00	
	31,25	3,20	0,75		18,75	2,94	0,58		4,68	1,65	0,71
	93,75	3,40			87,50	3,58			15,62	2,00	
Standard deviation			0,0115	**Standard deviation**			0,0251	**Standard deviation**			0,0601
Deviation %			1,5	**Deviation %**			4,3	**Deviation %**			8,5
Mean alfa			**0,74**	**Mean alfa**			**0,61**	**Mean alfa**			**0,77**
3	23,44	1,76	0,79	**3**	7,81	1,62	0,43	**3**	7,81	1,60	0,92
	62,50	2,00			56,25	1,93			14,06	2,10	
	23,44	1,76	0,84		7,81	1,78	0,46		6,25	1,68	0,85
	54,69	1,93			51,56	1,98			14,06	1,95	
	14,06	1,60	0,70		10,94	1,72	0,54		7,81	1,63	0,92
	48,44	2,00			57,81	2,00			14,06	2,10	
Standard deviation			0,0594	**Standard deviation**			0,0452	**Standard deviation**			0,0312
Deviation %			8,5	**Deviation %**			8,4	**Deviation %**			3,4
Mean alfa			**0,78**	**Mean alfa**			**0,47**	**Mean alfa**			**0,90**
4	18,75	1,70	0,75	**4**	7,81	1,50	0,56	**4**	7,81	1,50	0,92

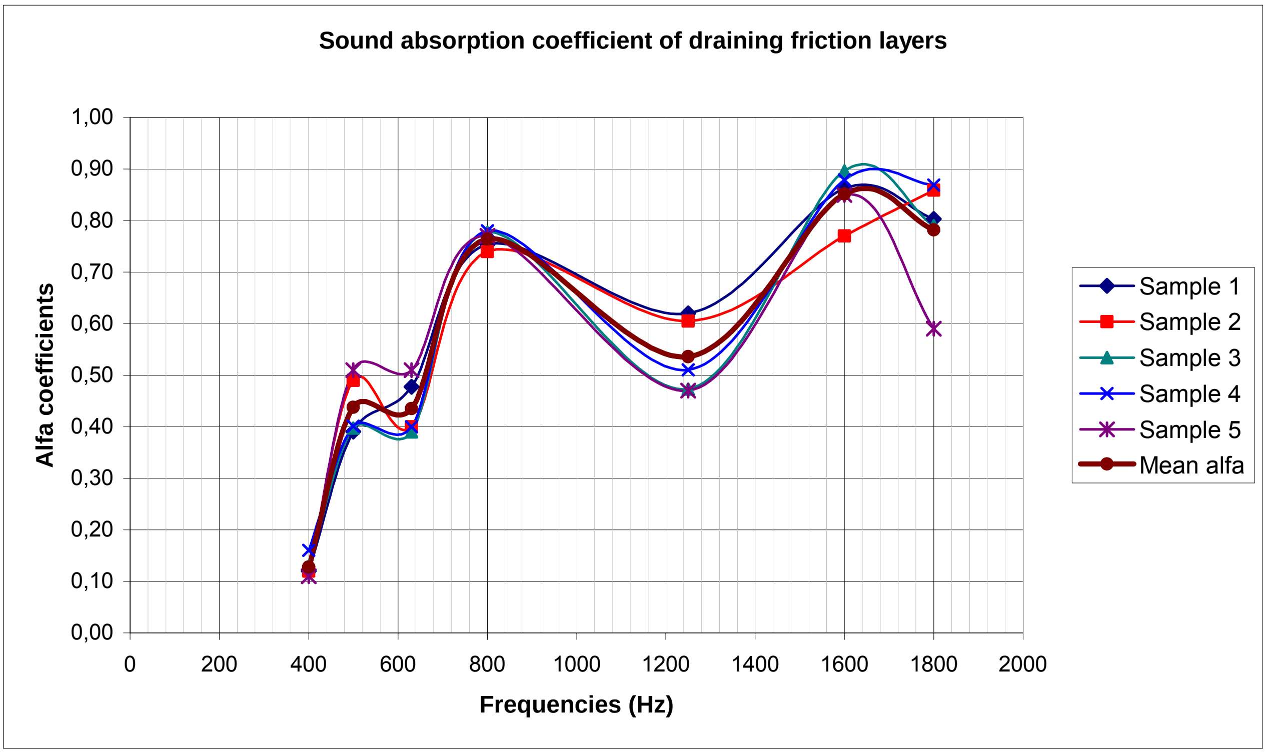
	56,25	2,00			39,06	1,95			14,06	2,10	
	18,75	1,60	0,84		7,81	1,70	0,48		7,81	1,82	0,83
	43,75	2,30			48,44	2,00			18,75	2,10	
	18,75	1,80	0,75		10,94	1,59	0,50		7,81	1,62	0,89
	56,25	2,00			64,06	2,10			15,62	2,00	
Standard deviation			0,0424	**Standard deviation**			0,0327	**Standard deviation**			0,0366
Deviation %			5,7	**Deviation %**			6,6	**Deviation %**			4,1
Mean alfa			**0,78**	**Mean alfa**			**0,51**	**Mean alfa**			**0,88**
5	25	1,78	0,76	**5**	7,81	1,38	0,51	**5**	7,81	1,64	0,86
	73,44	2,02			43,75	2,07			17,19	1,91	
	26,56	1,73	0,78		7,81	1,3	0,46		7,81	1,52	0,83
	73,44	2,15			51,56	2,03			18,75	1,87	
	26,56	1,75	0,78		7,81	1,35	0,44		7,81	1,49	0,86
	73,44	2,07			54,69	1,97			17,19	1,83	
Standard deviation			0,0105	**Standard deviation**			0,0326	**Standard deviation**			0,0136
Deviation %			1,4	**Deviation %**			7,4	**Deviation %**			1,6
Mean alfa			**0,77**	**Mean alfa**			**0,47**	**Mean alfa**			**0,85**
Mean alfa of 5 samples			**0,77**	**Mean alfa of 5 samples**			**0,54**	**Mean alfa of 5 samples**			**0,85**
Standard deviation of 5 samples			0,0148	**Standard deviation of 5 samples**			0,0656	**Standard deviation of 5 samples**			0,0435
Deviation % of 5 samples			1,9	**Deviation % of 5 samples**			12,2	**Deviation % of 5 samples**			5,1

DETERMINATION OF SOUND ABSORPTION COEFFICIENT KUNDT'S TUBE- DRAINING FRICTION LAYER Frequency 1800 (Hz)			
Sample N°	FREQUENCY (Hz)		**1800**
	Vp-p	Vavg	**Alfa**
1	7,80	1,70	0,83
	18,75	1,80	
	6,25	1,80	0,75
	18,75	1,80	
	7,80	1,50	0,83
	18,75	1,80	
Standard deviation			0,0377
Deviation %			4,5
Mean alfa			**0,80**
2	7,80	1,75	0,86
	17,20	1,80	
	7,80	1,60	0,89
	15,62	1,76	
	7,80	1,80	0,83
	18,75	1,92	
Standard deviation			0,0239
Deviation %			2,9
Mean alfa			**0,86**

3	7,81	1,58	0,83
	18,75	1,91	
	7,81	1,55	0,83
	18,75	1,92	
	4,68	1,72	0,71
	15,62	1,97	
Standard deviation			0,0569
Deviation %			8,0
Mean alfa			**0,79**
4	7,81	1,78	0,89
	15,62	2,30	
	7,81	1,70	0,86
	17,19	2,00	
	7,81	1,82	0,86
	17,19	2,00	
Standard deviation			0,0140
Deviation %			1,6
Mean alfa			**0,87**
5	7,81	1,68	0,59
	35,94	2	
	7,81	1,66	0,60
	34,36	2,1	
	7,81	1,75	0,59
	35,94	2,1	
Standard deviation			0,0080
Deviation %			1,4
Mean alfa			**0,59**
Mean alfa of 5 samples			**0,78**
Standard deviation of 5 samples			0,1000
Deviation % of 5 samples			12,8

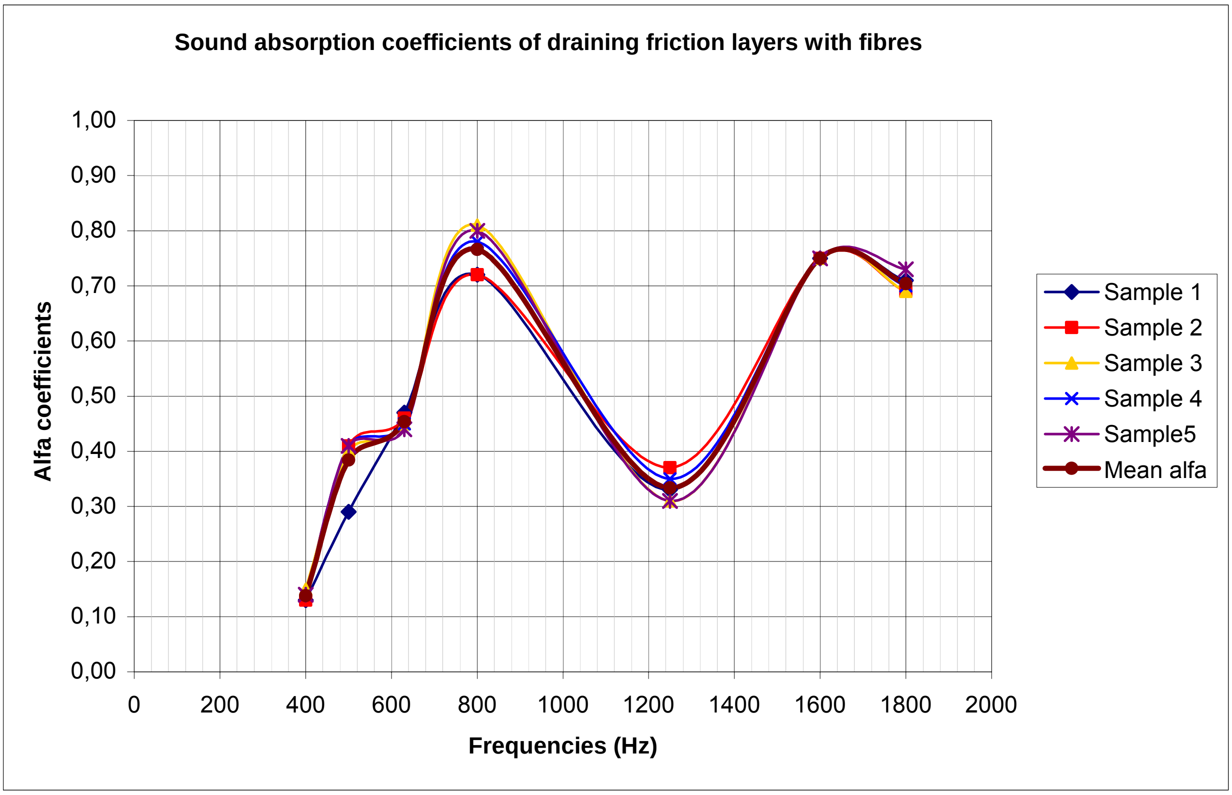
The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
1	0,12	0,39	0,48	0,75	0,62	0,86	0,80
2	0,12	0,49	0,40	0,74	0,61	0,77	0,86
3	0,13	0,40	0,39	0,78	0,47	0,90	0,79
4	0,16	0,40	0,40	0,78	0,51	0,88	0,87
5	0,11	0,51	0,51	0,77	0,47	0,85	0,59
Mean alfa	**0,13**	**0,44**	**0,44**	**0,76**	**0,54**	**0,85**	**0,78**



Draining mixture with fibres (D.M.F.)

The experimental results, whose protocol is written in paragraph § 4, are synthetically written in the following table and diagram.

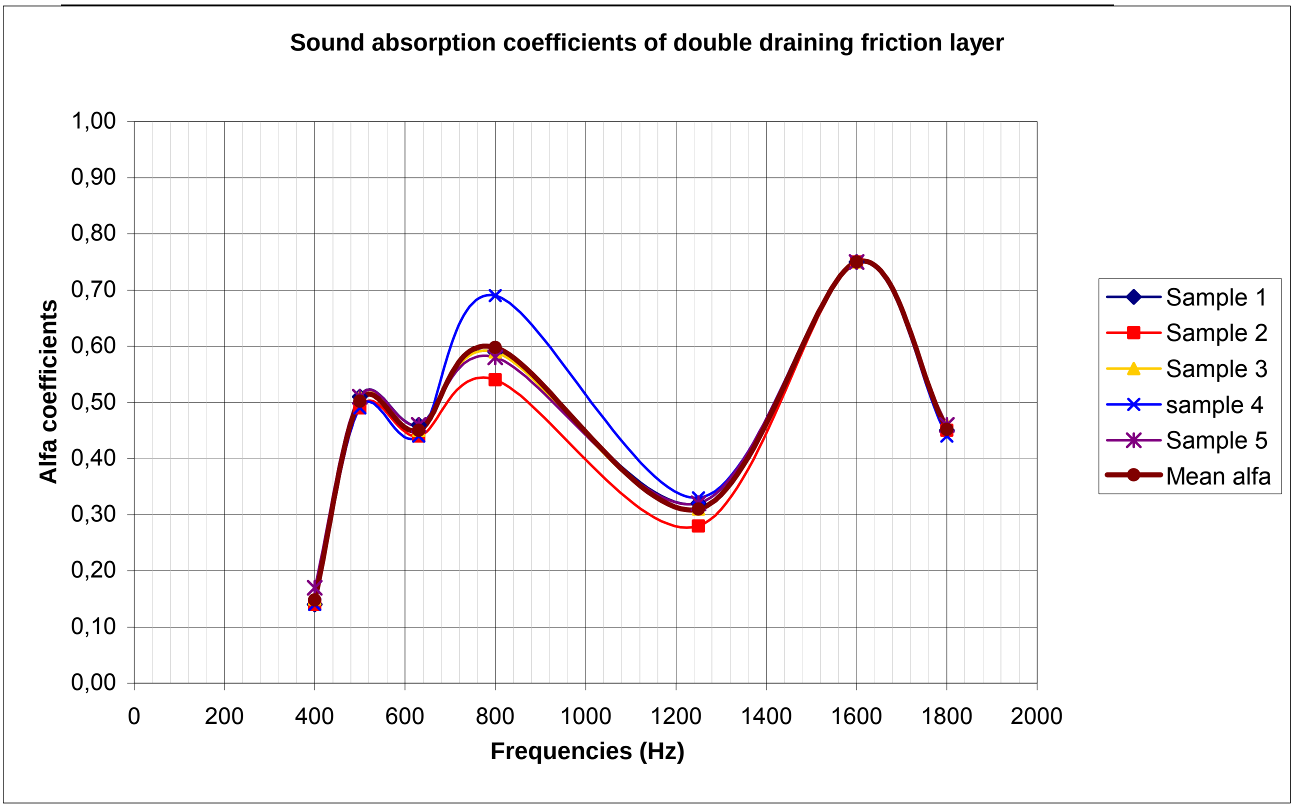


Double draining layer mixture (D.D.L.M.)

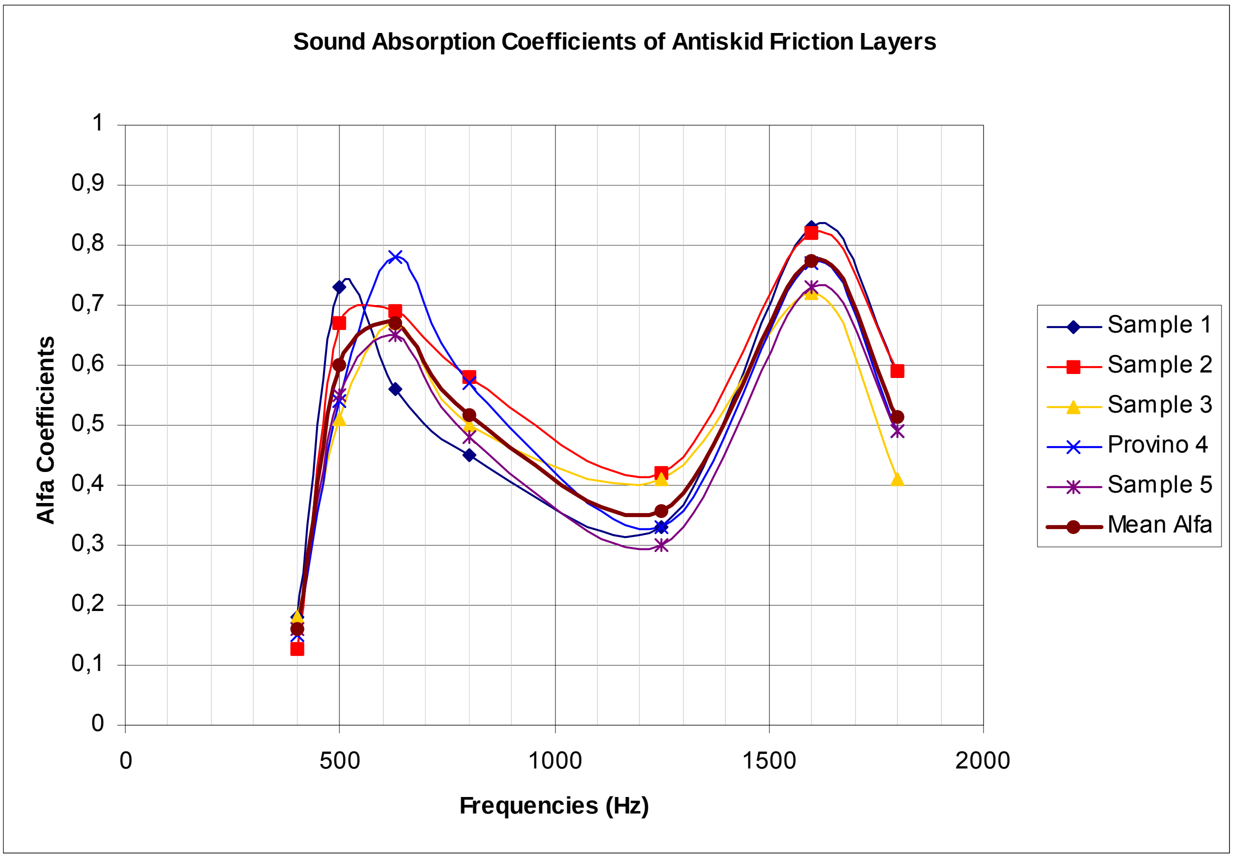
The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

Antiskid mixture (A.M.)

The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.



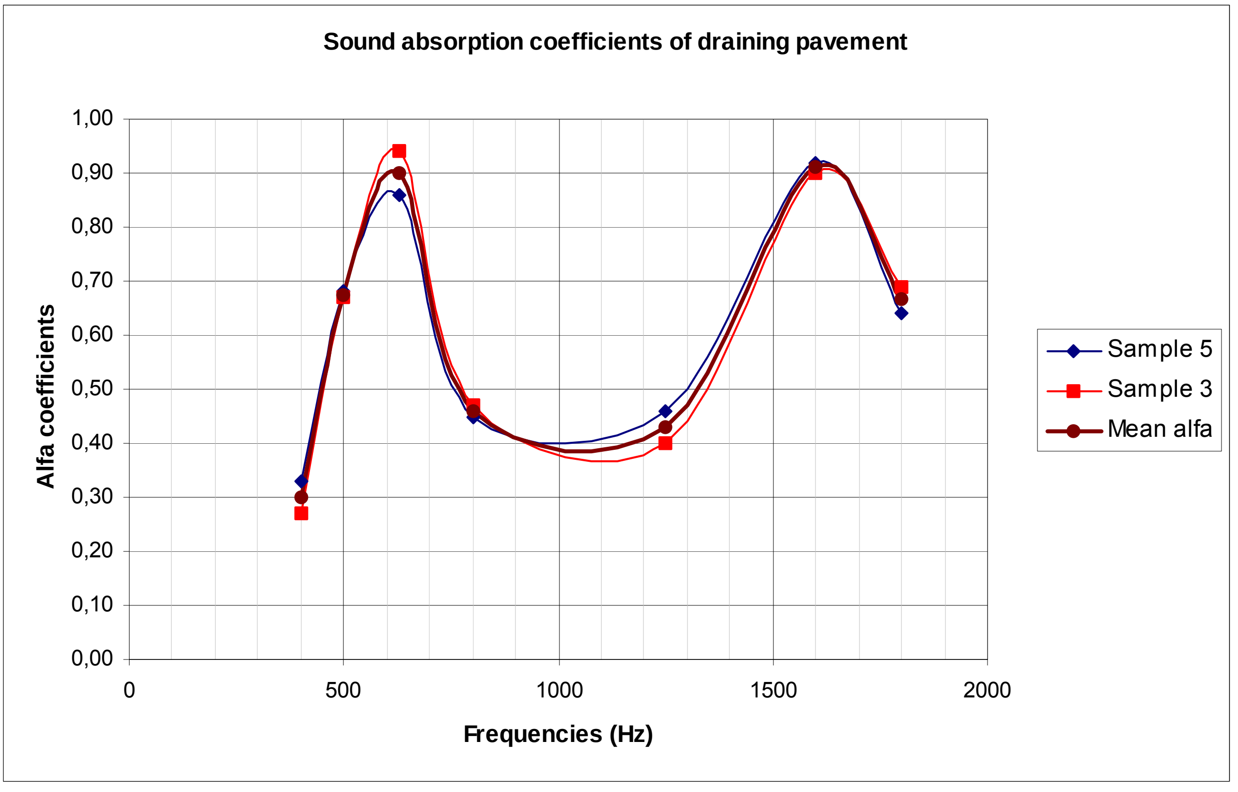
Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	**500**	**630**	**800**	**1250**	**1600**	**1800**
1	0,18	0,73	0,56	0,45	0,33	0,83	0,59
2	0,13	0,67	0,69	0,58	0,42	0,82	0,59
3	0,18	0,51	0,67	0,5	0,41	0,72	0,41
4	0,15	0,54	0,78	0,57	0,33	0,77	0,49
5	0,16	0,55	0,65	0,48	0,30	0,73	0,49
Mean alfa	**0,16**	**0,60**	**0,67**	**0,52**	**0,36**	**0,77**	**0,51**



Draining pavement (D.P.)

The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

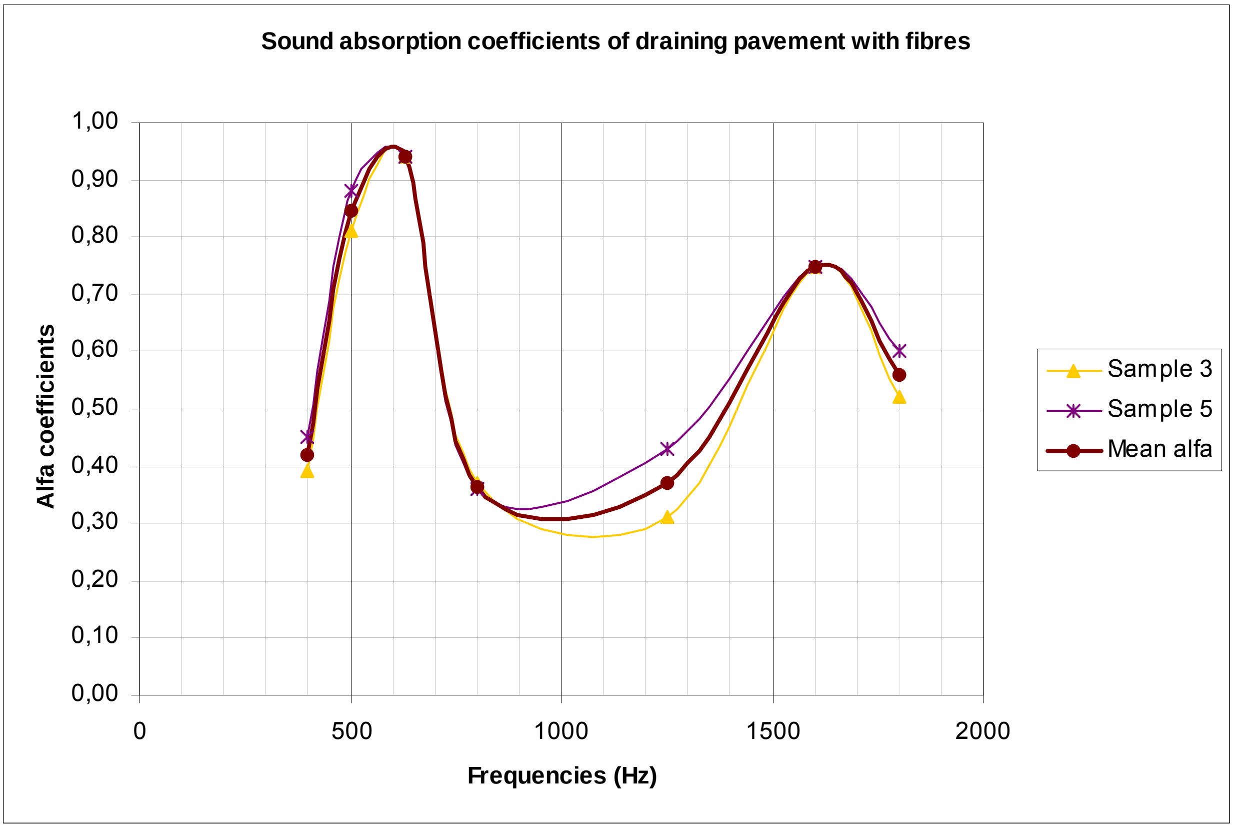
Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
1	0,33	0,68	0,86	0,45	0,46	0,92	0,64
2	0,27	0,67	0,94	0,47	0,4	0,9	0,69
Mean alfa	**0,30**	**0,68**	**0,90**	**0,46**	**0,43**	**0,91**	**0,67**



Draining pavement with fibres (D.P.F.)

The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

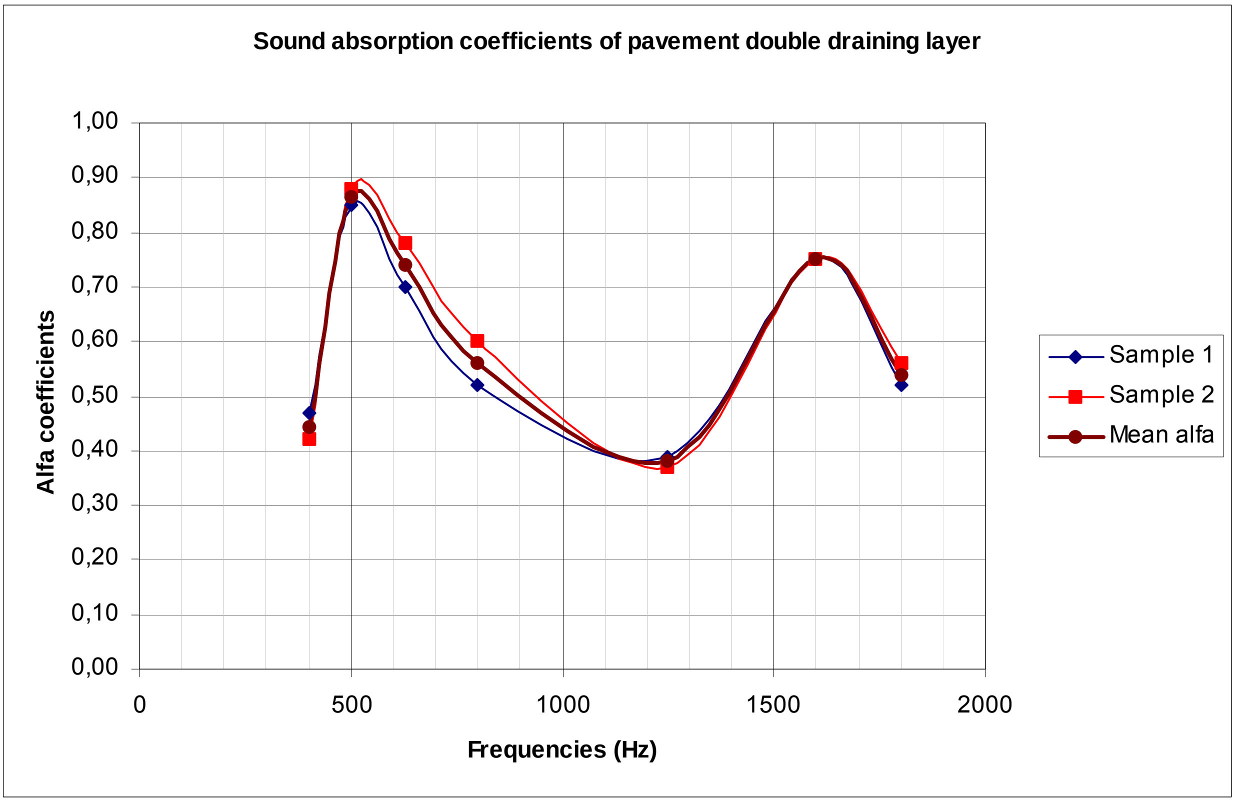
Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
3	0,39	0,81	0,94	0,37	0,31	0,75	0,52
5	0,45	0,88	0,94	0,36	0,39	0,75	0,60
Mean alfa	**0,42**	**0,85**	**0,94**	**0,37**	**0,35**	**0,75**	**0,56**



Double draining layer pavement (D.D.L.P.)

The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

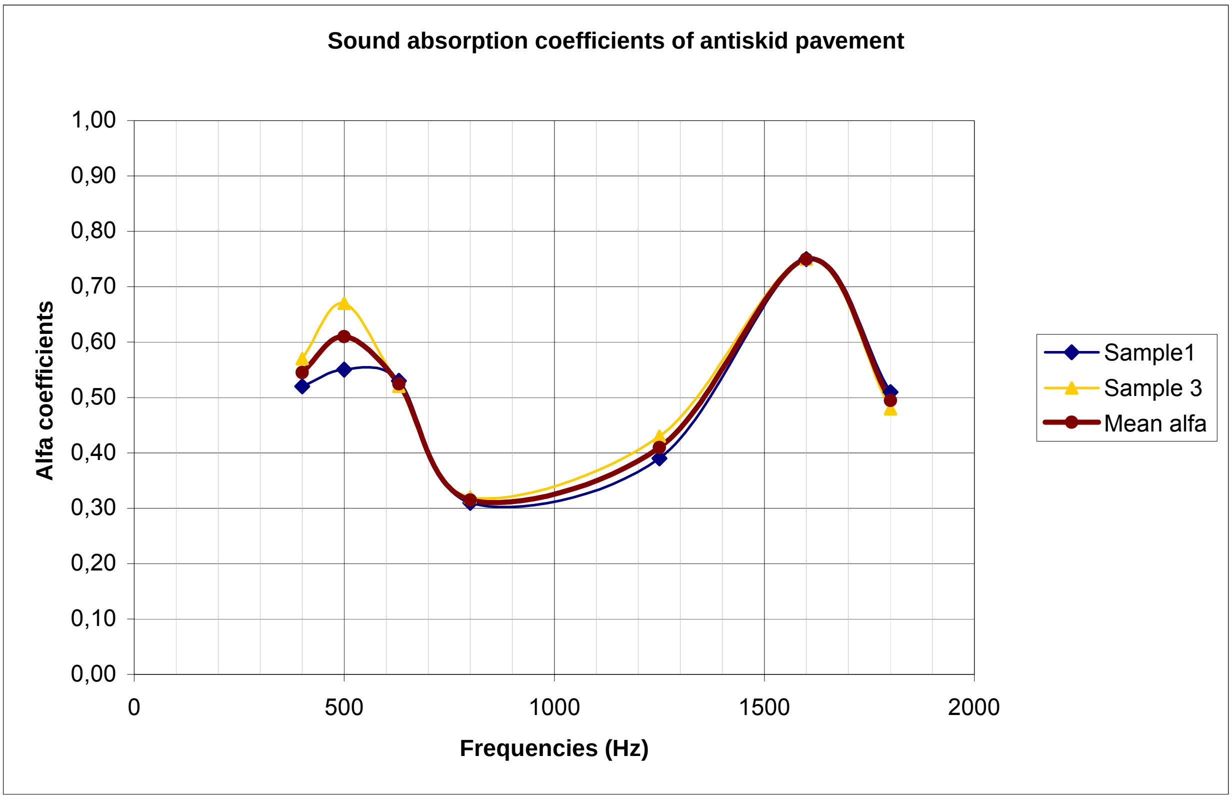
Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
1	0,47	0,85	0,7	0,52	0,39	0,75	0,52
2	0,42	0,88	0,78	0,6	0,37	0,75	0,56
Mean alfa	**0,45**	**0,87**	**0,74**	**0,56**	**0,38**	**0,75**	**0,54**



Antiskid pavement (A.P.)

The experimental results, whose protocol is written before, are synthetically written in the following table and diagram.

Sample n°	SOUND ABSORPTION COEFFICIENT						
	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
1	0,52	0,55	0,53	0,31	0,39	0,75	0,51
3	0,57	0,67	0,52	0,32	0,43	0,75	0,48
Mean alfa	**0,55**	**0,61**	**0,53**	**0,32**	**0,41**	**0,75**	**0,50**

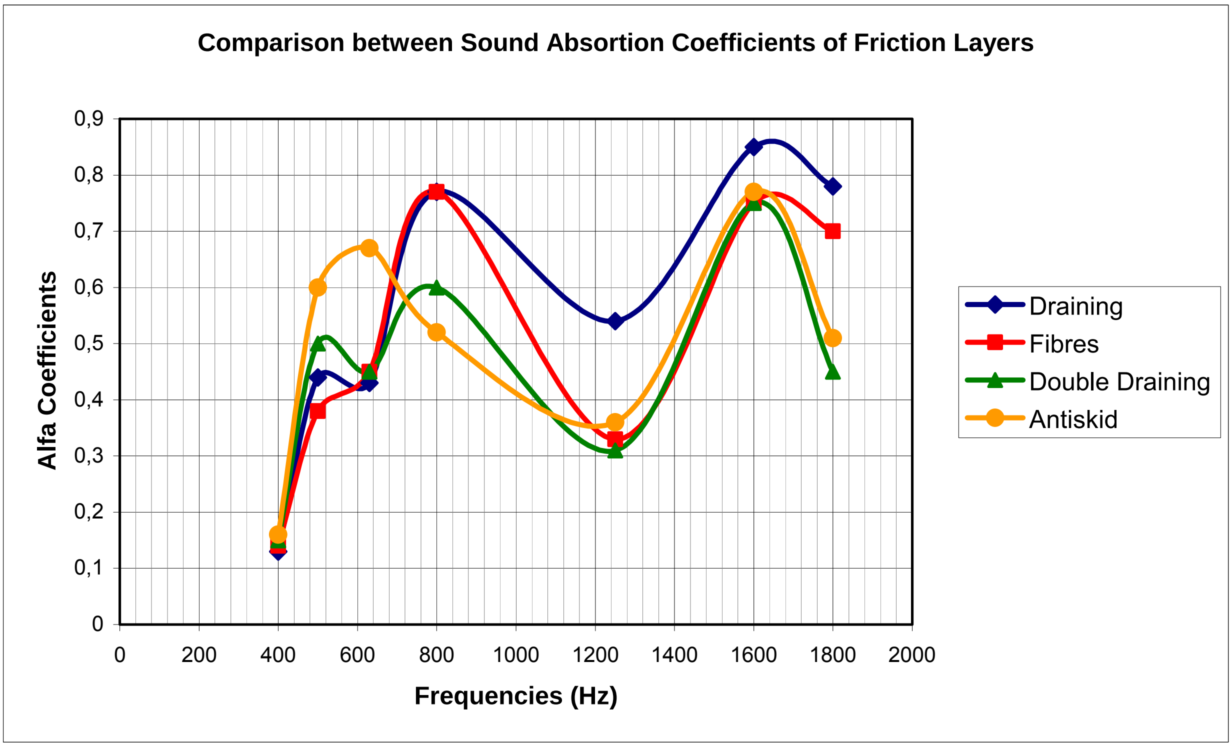


ANALYSIS OF THE RESULTS

The experimental results on friction layers and friction layers with binder courses are written together in the following diagram in order to evaluate better the sound absorption characteristics of the mixtures used at different frequencies.

Friction layers

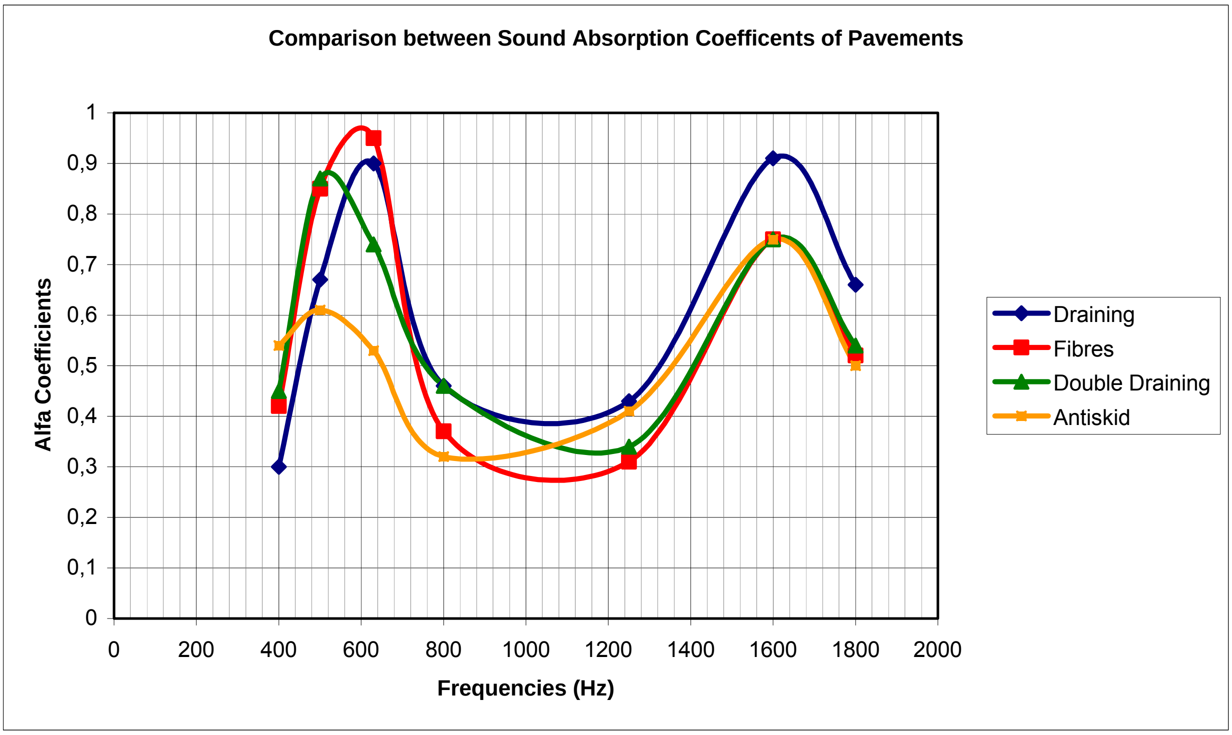
SOUND ABSORPTION COEFFICIENTS OF FRICTION LAYERS							
Friction layers	**Frequencies (Hz)**						
	400	**500**	**630**	**800**	**1250**	**1600**	**1800**
Draining	0,13	0,44	0,43	0,77	0,54	0,85	0,78
Draining with fibres	0,14	0,38	0,45	0,77	0,33	0,75	0,70
Double draining layer	0,15	0,50	0,45	0,60	0,31	0,75	0,45
Antiskid	0,16	0,60	0,67	0,52	0,36	0,77	0,51



The experimental results of the friction layers, synthetically written in the previous diagram, show a variety of responses of each mixture at each frequency.
In all the mixtures, in fact, the absorption coefficient values are higher at 800 and 1600 Hz, whereas they tend to decrease at intermediate frequencies.
It seems evident that draining mixtures with and without fibres provide the best performances.

Pavements

SOUND ABSORPTION COEFFICIENTS OF PAVEMENTS							
Pavement	Frequencies (Hz)						
	400	500	630	800	1250	1600	1800
Draining	0,30	0,67	0,90	0,46	0,43	0,91	0,66
Draining with fibres	0,42	0,85	0,95	0,37	0,35	0,75	0,52
Double draining layer	0,45	0,87	0,74	0,56	0,38	0,75	0,54
Antiskid	0,54	0,61	0,53	0,32	0,41	0,75	0,50



The experimental results of the friction layer-binder course system reveal the substantially positive contribution of the bottom layer to the sound absorption capabilities of the different mixtures.
The substantial increase of the sound absorption coefficient α values of all the mixtures and at the different frequencies is shown by the analysis of the curves written in the previous diagram.
In particular, this increase of the sound absorption coefficient of the double draining layer mixture especially at intermediate frequencies is evident.

CONCLUSIONS

The experimentation has pointed out that pavements with a high percentage of air voids present higher characteristics of acoustic absorption of incident acoustic waves, in fact, the antiskid mixture which has a mean porosity value equal to 6.8 %, much lower than the values of the other mixtures, has a lower sound absorption coefficients α.
The diagrams that show the comparison between the acoustic performances of the different mixtures (with and without binder) prove that the effect of the acoustic pressure reduction is more evident at frequencies of 800 and 1600 Hz.
Using the sound absorption coefficient α as a parameter of the sound absorption properties of the different mixtures is correct [16], although this parameter does not consider the effective reflection angle of the acoustic waves on the road surface, because this coefficient is measured in the case of normal incidence.

The development of this research provides a methodology which can be an alternative instead of the Kundt's tube and which can be able to consider the effective mechanisms that generate traffic noise, as the interference between the acoustic waves interacting directly with the pavements and the reflected waves.

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