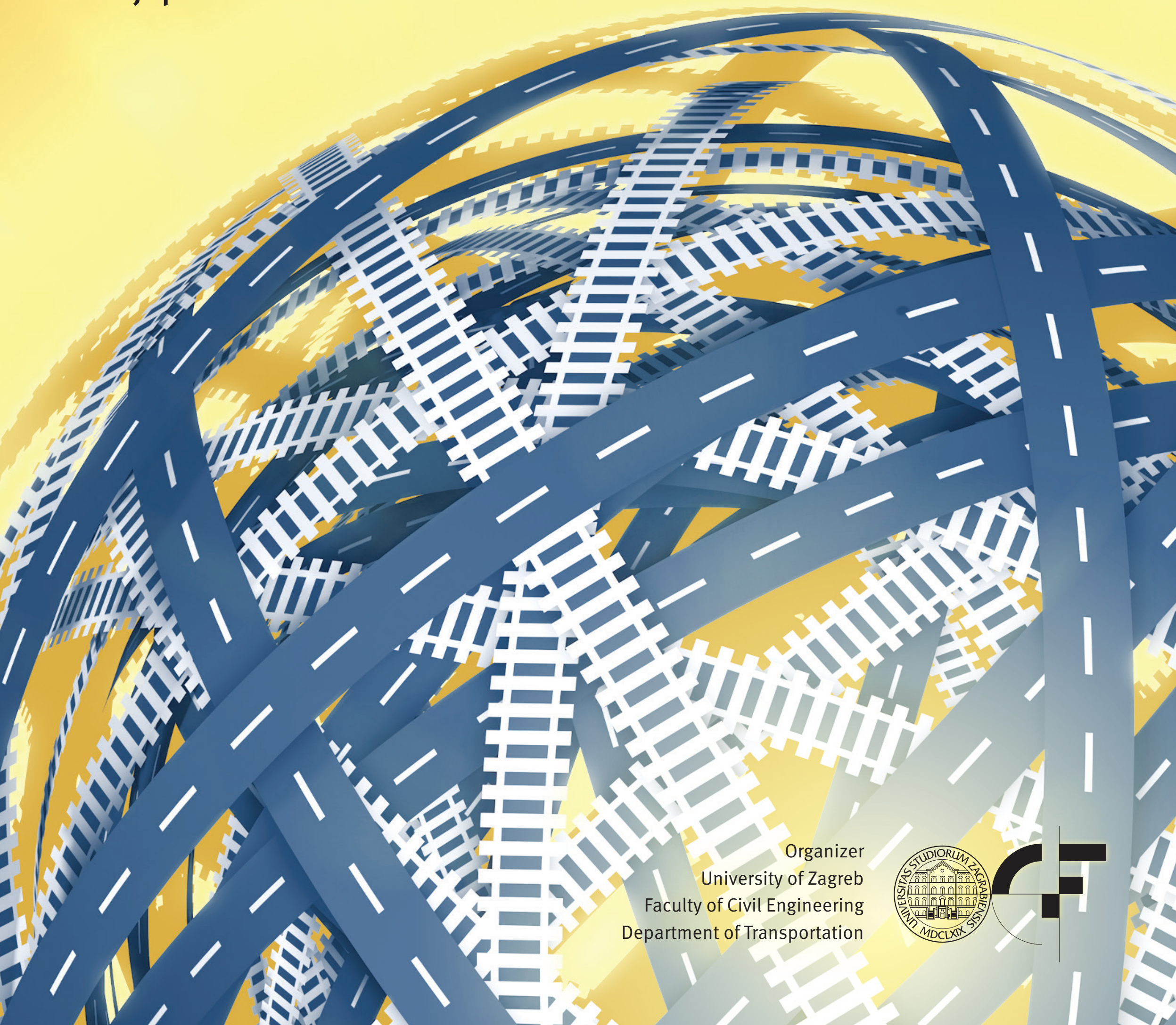
CETRA 2016

4th International Conference on Road and Rail Infrastructure
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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Road and Rail Infrastructure IV

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VIBRATION-NOISE-CANCELLING ASPHALT PAVEMENT: INNOVATION FOR SILENT CITIES

Loretta Venturini, Sergio Carrara
ITERCHIMICA, Italy

Abstract

There are different factors that can affect the life quality and involve different areas of human activity, especially in urban areas. Noise and vibration are two elements to which people are more susceptible, because sometimes they can affect the physical and mental well-being. The process of industrialization and motorization can be considered as the main reason for the existence of these two factors. For example, the vibrations generated by road traffic, as well as being a source of trouble for residents, can cause damage to buildings and equipment in the areas close to roads. Sometimes it interferes with activities such as those carried out in operating rooms or in precision laboratories. Several legislative solutions have been undertaken in recent years, to decrease road noise, even if the efforts to reduce vibrations are not appropriate to the level of damage done. Experts and researchers around the world have been studying solutions aimed at the mitigation of these disturbing elements. Interesting studies have been carried out on road paving construction materials which are be capable of reducing vibrations caused by road traffic.Iterchimica's researchers have developed a special technology based on the use of rubber powder derived from recycled tyres at the end of their service life, which can reduce vibration and the resulting rolling noise. In reference to the latter the results of a study conducted in collaboration with iPOOL srl, a spin-off of the Italian National Research Council (CNR) are reported.

Keywords: noise mitigation; crumb rubber; anti-vibration

1 Introduction

The traffic represents an important source regarding the noise pollution affects all the urban areas inside a city. Each vehicle running over the asphalt pavement becomes a noise source in movement. It's possible to follow different strategies in order to reduce the traffic noise that can be divided in 2 groups:
• Active Solutions focused on the noise reduction at the source level;
• Passive Solutions focused on the noise energy limitation before who is the receiver.

The vehicle manufacturers can work on all noise parameters connected with the mechanic components while the pavement designers have to focus on the power noise reduction coming from the tyre-pavement interaction. Rolling tyre noise and vibrations are among the most important sources disturbing the life quality in urban areas; it is on these parameters that the asphalt and pavement designers have to work, introducing new technologies. The use of a particular compound prepared by using selected crumb rubber and special polymers can reduce the tyre rolling noise and the vibrations generated by the vehicular traffic.

2 Vibrations caused by traffic

The vehicular action generates vibrations and noise; the sources are: engine, air resistance, tyre rolling on the surface, as well as use of the brakes. In addition, other noises are produced depending on pavement surface that is never perfectly smooth and flat, due to the laying procedure, the technology used and the presence of surface damages.
The result of these actions causes an oscillatory movement in the vehicle, disturbing the users on board, and the energy waves that propagate in the pavement structure reach the structure and the person who lives inside. It is also very important to know that the transfer of vibrations from the source to the receiving point takes place in different phases, during which the vibrational waves are modified before being retransmitted (Fig. 1).

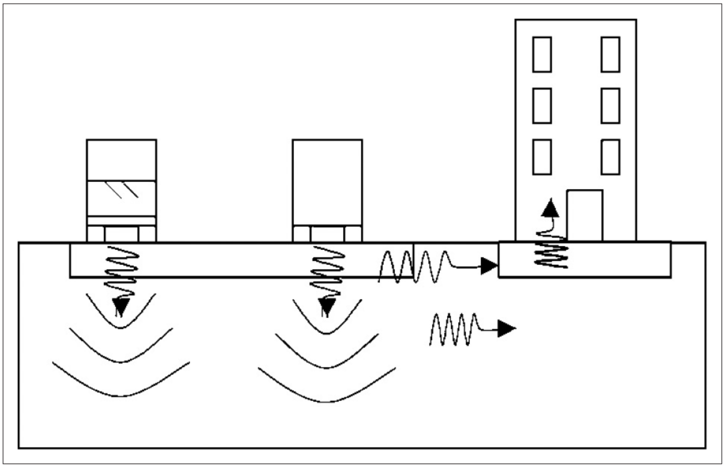

Figure 1 Scheme of transmission of traffic vibrations

Anyway, the interaction between road surface and vehicle can be considered an emitting source in the range of the low-mid frequency (<1000 Hz approximately). Over the past 20 years, some researches have shown that the structure of the pavement has a strong influence on the rolling tyre noise and vibrations. The rolling tyre noise depends on two main factors:

1) The maximum size of the aggregates and the aggregate gradation used in the asphalt mix: Using negative surface texture it's possible to reduce the rolling tyre noise thanks to the reduction of the air pumping effect;
2) Reducing the pavement stiffness it's also possible to mitigate the vibrational noise component;

Regarding vibrations the most influential physical-mechanical characteristics are stiffness and damping capacity. Therefore, the anti-vibration pavement must be studied considering and changing those two elements.

3 Anti-Vibration pavement using robber powder

3.1 Optimization of the pavement texture

Researchers have shown that, in order to reduce the noise emission from rolling and vibration, the texture should be optimized according to the following general characteristics:

- the micro-texture ($\lambda < 0.5$ mm) must be increased, in order to reduce the noise due to air pumping (the air will be compressed and expanded inside this micro texture structure);

- the macro-texture (0.5 ‹ λ ‹ 50 mm) must be composed by high amplitudes in the range of wavelengths 1-8 mm, instead the amplitudes should be low in the range 10-50 mm (reduction of the noise component due to the vibratory phenomenon);
- the maximum diameter of the aggregates in the mixture should not be more than 8 mm in order to obtain layer with low-noise and vibration (in any case, the maximum diameter should not be more than 10 mm);
- the aggregates shall be crushed in order to increase the texture levels at low wavelengths;
- the texture must be negative; the road profile has a negative texture when it is characterized by valleys (Fig. 2-3).

Figure 2 Positive texture of the road surface

Figure 3 Negative texture of the road surface

- the pavement must have a homogeneous macro-texture;
- the aggregates used must have cubic shape so the orientation does not affect the values of mega-texture (50 mm ‹ λ ‹ 500 mm) that can influence the vibration.

3.2 Optimization of the sound absorption and vibration of material for road pavement

In order to design a new anti-vibration material it is important to consider that:
1) The frequency of maximum absorption must lie at the frequencies of maximum emission (this frequency is about 1000 Hz for roads with high driving speed, while is around 600 Hz for those at low speeds);
2) The vibration wavelengths that affect the buildings and their inhabitants are included between 10 and 300 Hz;
3) The absorption spectrum must be large enough to dissipate the noise emission in a frequency range that is as wide as possible;
4) Materials such as bituminous mastic and rubber confer elasticity in order to absorb mechanical energy, damping the oscillations induced by the passage of vehicles and the resulting vibrations.

Especially concerning the last point, the pavement designer can introduce new innovative technologies in order to add in to project a possible solution to reduce the vibration made by the traffic.

4 No-noise pavement using robber powder

The studied no-noise bituminous mixture for wearing course is made by a mixture of crushed aggregates, sand, filler, bitumen and polymeric compound with rubber powder. It allows the reduction of the noise emission thanks to the optimized texture and the reduction of vibration transmission due to the stiffness studied.

The bitumen used 50/70 penetration (classified according to UNI EN 12591) in a dosage ranging between 6.5 – 8 % on the weight of the mixture.
The bituminous mixture studied is a gap graded type with a discontinuous gradation studied to reduce the rolling tyre noise, linked by a mastic characterized by a high viscosity and composed of bitumen, filler and polymer compounds to reduce the final mixture stiffness and the vibrations connected. This polymeric compound is made with a mixture of rubber powder especially studied and different polymers and it must be dosed at 2-4% on the weight of the aggregates, Figure 4.

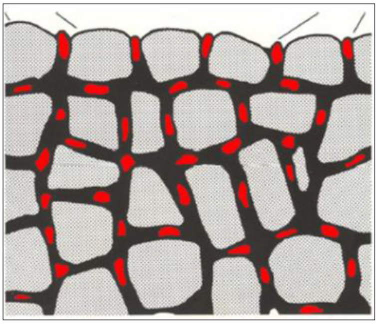

Figure 4 Representative image of the mixture with the added compound

Using this technology it's possible to act on the following prameters:
- The polymeric compound creates a bituminous mastic guaranteeing a reduced emission of the acoustic vibrations generated by traffic;
- The proper granulometric curve studied has the function of creating a proper superficial texture guaranteeing a reduced emission of the rolling noise generated by the tyre-paving contact

4.1 Mix production

The production technique of this technology is similar to the conventional asphalt concrete and it's called "dry method". The compound has to be added directly in the mixer for batching plants, after the hot aggregates or, in case of continuous plants, during the final stage of mixing. The precautions required are the temperature and the mixing time. In fact, the mixing process must take place at temperatures between 170 and 180 ° C to allow the polymeric component to complete its dissolution and facilitate the laying of the modified asphalt concrete.

5 CASE HISTORY n° 1: Alessandria province s.p. 82 (Municipality of "Alluvioni Cambiò-Grava") – Noise Reduction

The road SP n° 82 "Spinetta-Sale" passes trough the Municipality of Alluvioni Cambiò, that has been built all around this main street (Fig. 5). During the last years people living near this road have put in evidence a problem connected with the traffice noise, certified later by a noise analysis done by ARPA Piemonte (Agenzia Regionale per la Protezione dell'Ambiente – Piemonte Region). This analysis has underlined that the traffic noise in that place is over the limits defined in the regional specifications. In this case the application of noise barriers was not possible because the houses were built close to the street with no space for this type of application. The only possible solution was the noise reduction thanks to the use of a particular technology for asphalt mix with the use of a rubber powder compound and different polymers added directly in the asphalt mixture during the producion of the wearing course. The old wearing course has been replaced with this new.

Figure 5 Job site location

Also the speed distribution has been analyzed during the noise registrations and, in the following figure (Fig. 6), it's possible to verify that 50 km/h was the most common speed. This parameter is important because it's connected with the noise frequency.

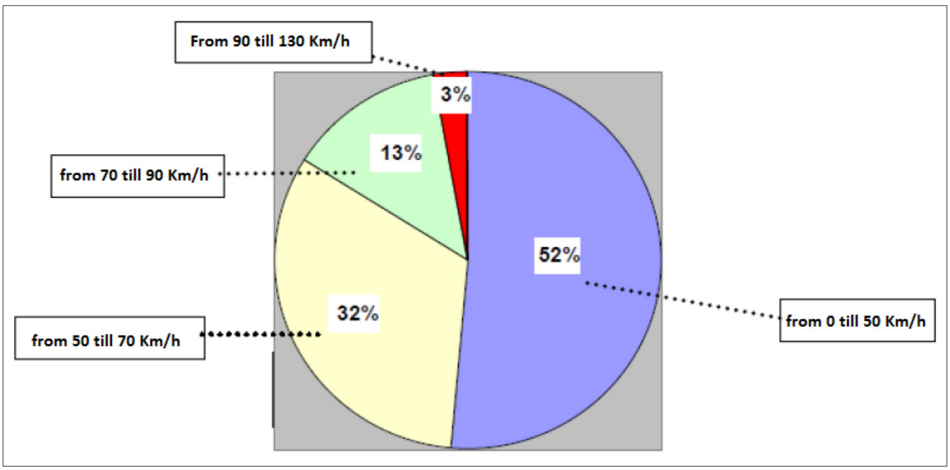

Figure 6 Speed distribution

The noise measured during the analysis has been compared with the limits applied in that area (Fig. 7) and with the results measured after the application of the no-noise asphalt wearing course. In fact the noise analysis has been repeated 6 months after from the application of the asphalt pavement.

STANDARD ***DPR 30/03/2004***	
DAY (6:00 – 22.00) [dB]	NIGHT (22.00 – 6.00) [dB]
70	60

Figure 7 Noise limits for the urban area

5.1 Job Mix Formula

The asphalt mix used has been studied with a discontinuous gradation (Fig. 8) and the voids have been filled by the rubber mastic. The final job mix formula has been the following:
• 7,5% Bitumen on the aggregates weight;
• 3% of compound made using rubber powder and different polymers;

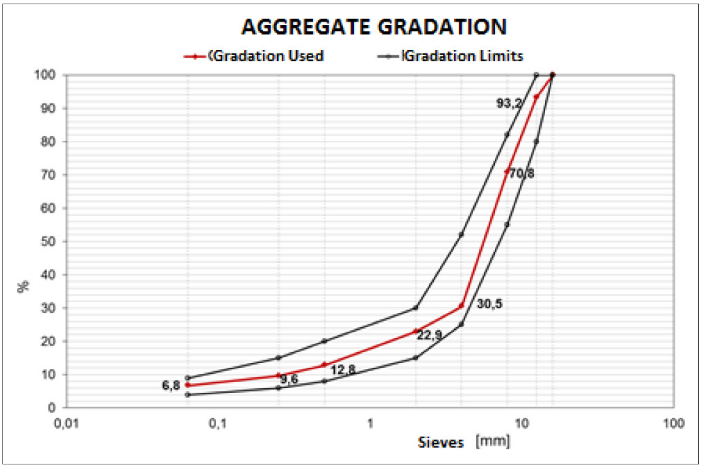

Figure 8 Aggregates gradation

5.2 Application of the no-noise wearing course

Some pictures of the application are reported below, Figures 9, 10 and 11:

Figure 9 Laying of the wearing course

Figure 10 Laying of the wearing course and compaction with roller

Figure 11 After the application

5.3 Noise Analysis

Before the application of this no-noise wearing course, a lot of noise measurements have been done. Every day the instrumentation has registered the average noise level during the day (from 6.00 am to 10.00 pm) and night (from 10.00 pm to 6.00 am). The microphone has been located at a high of 3 m near one house as requested from the standard EN 60651 and EN 60804. The results are expressed in dB(A) and they are reported in the following Table 1:

Table 1 Leq before the application of the new wearing course

	Mon.	**Tue.**	**Wed.**	**Thur.**	**Fri.**	**Sat.**	**Sun.**
Leq, day [dB(A)]	**70,4**	70,0	69,8	**70,3**	**70,2**	69,7	68,2
Leq, night [dB(A)]	**64,9**	**61,7**	**62,6**	**62,6**	**66,0**	**65,6**	**86,8**

The values in red represent the days when the limit is overpassed. Considering the weekly average, the result is the following Table 2:

Table 2 Weekly Leq before the new wearing course

	WEEKLY VALUE
Leq, day [dB(A)]	69,8
Leq, night [dB(A)]	**64,3**

The weekly value was near the limit during the day while it was higher during the night. After 6 months from the application of the wearing course, using the no-noise technology, the noise analysis has been repeated. The results are reported in the following Table 3:

Table 3 Leq after the application of the new wearing course

	Mon.	**Tue.**	**Wed.**	**Thur.**	**Fri.**	**Sat.**	**Sun.**
Leq, day [dB(A)]	61,5	60,2	62,7	62,6	61,9	60,9	68,2
Leq, night [dB(A)]	53,6	52,5	53,9	51,0	58,4	**61,4**	59,1

After the application of the new wearing course, only on Saturday night the limit was overpassed. The application has achieved its scope. If we consider the weekly average the result is the following Table 4:

Table 4 Weekly Leq after the new wearing course

	WEEKLY VALUE
Leq, day [dB(A)]	63,4
Leq, night [dB(A)]	57,2

The weekly situation clearly show the benefits of the application. The limits are respected both during the day and during the night. The most important parameter in order to understand the noise reduction made using the no-noise technology is the difference before the application of the wearing course and after it. The weekly different registered is the following Table 5:

Table 5 Weekly difference between Leq Before and After the application of new wearing course

	WEEKLY DIFFERENCE
ΔLeq, day [dB(A)]	- 6,4
ΔLeq, night [dB(A)]	- 7,1

Thanks to this technology it was possible to reduce the traffic noise of about 7 dB(A). This reduction has clearly shown the benefits of this application in terms of noise pollution for the people leaving around that urban area.

6 CASE HISTORY n°2: Novara (Kennedy and Vercelli Streets) – Anti-Vibration Pavement

In order to limit the vibration produced by the vehicle passages, it has been applied a wearing course made following the specification of the no-noise asphalt mixture and using a compound of rubber powder and different polymers directly added into the asphalt mixture. The application has been done in a main road of Novara and it has been monitored using a vibration measurements made by some accelerometers. The location of the project has reported in the following figure (Fig. 12).

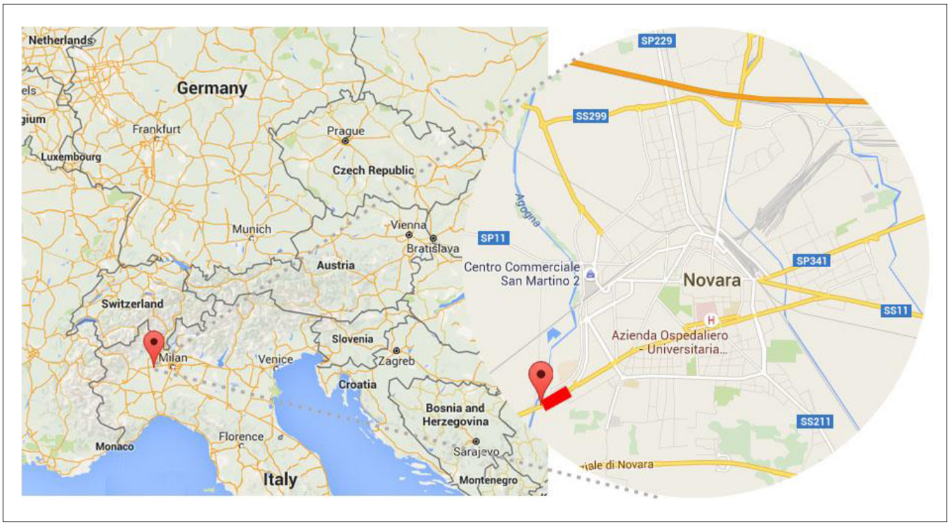

Figure 12 Job site location

The phases of realization were the following:

- Laboratory Mix Design Analysis;
- Production and laying of this new asphalt mixture between April and May 2014;
- Monitoring the anti-vibration performance during November 2014 and March 2015.

6.1 Job Mix Formula

After the tests of physical characterization, the final grading curve of the asphalt mix has been analyzed in order to determine the correct proportioning of the aggregates according to the grading reference (Fig. 13).
In order to optimize the bitumen content and verify the mechanical performance of the mixture in the laboratory (EN 12697-35) three mixtures have been prepared having different bitumen contents with a fixed percentage of polymeric compound equal to 2.5% on the weight of the aggregates. Especially, we have put in evidence the Indirect Tensile Strength according to EN 12697-23. Above the results achieved (Table 6).
Looking at the results it is possible to observe that the values are nearly equal for all three mixtures (typical behavior of this technology and verified in other experience), the choice of the optimum percentage of bitumen was determined in function of the lower percentage of voids and the greater stiffness: the optimal bitumen percentage is the number 3 in the table above equal to 7,24% on the aggregates weight.

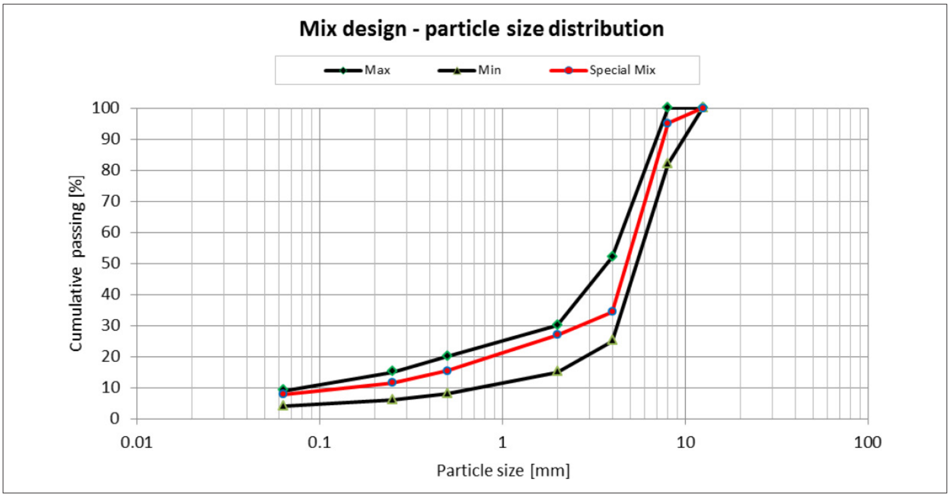

Figure 13 Aggregates gradation used

Table 6 Indirect Tenisli Strenght at different bitumen contents

Mixture	Bitumen content [% on mixture weight]	ITS [MPa]	CTI [MPa]	Axial displacement [mm]	Specific weight [kg/m³]	Average voids [%]
Limits	6 ÷ 8.5	≥ 0.45	---	---	---	› 2
1	6.39	0.92	53.6	2.613	2428	3.3
2	6.82	0.91	47.5	2.424	2414	3.2
3	7.24	0.88	38.0	3.206	2.411	2.7

6.2 Application of the no-noise wearing course

Some pictures of the application are reported here below (Figures 14 to 16):

Figure 14 Laying of the wearing course and compaction with roller

Figure 15 Wearing Course after compaction

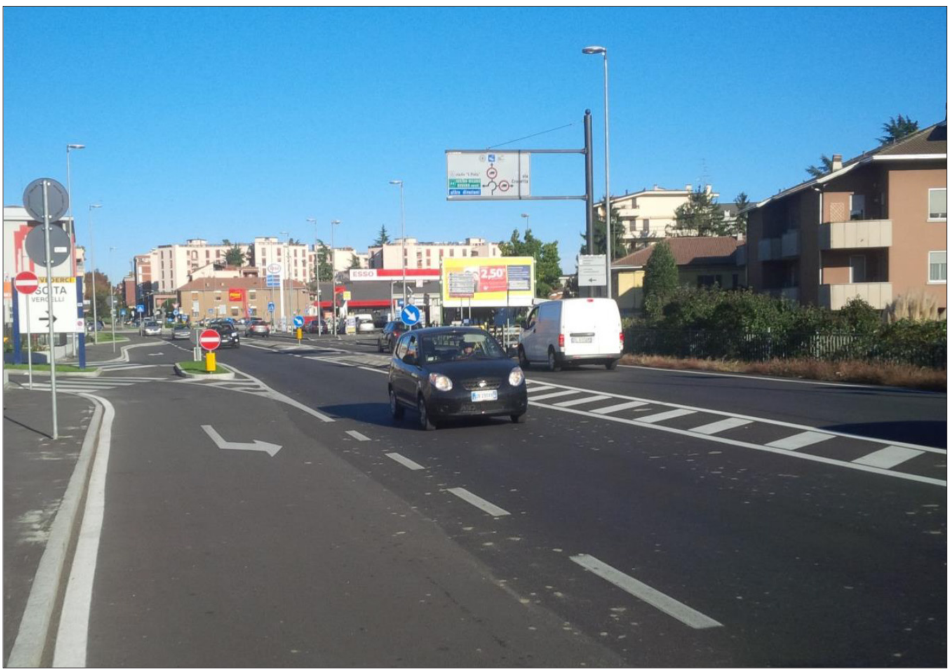

Figure 16 Corso Vercelli Street 3 months after construction

6.3 Vibration measurements and results

The vibration measurements were made on 23 November 2014 and 31 March 2015 in Corso Vercelli and Via Kennedy located in Novara. Purpose of the reliefs was to certify the pavement from the anti-vibrational point of view, and then compare it to the standard pavement. Both pavements haven't shown any surface damage that could generate abnormal vibration after the passage of vehicles.
The measurement method adopted follows a protocol currently under development that consist of acquisition of the vibration signal with an accelerometer station, which is connected solidly to the road surface analyzed (Fig. 17). The passage of a vehicle creates vibrations on the pavement, that are transmitted to the edge of the road, where they are evaluated through acceleration measurement devices in function of the time.
To overcome the inability to control the variables connected to the source (real traffic), it was chosen to analyze the signal resulting from the passage of two well-known and constant vehicles. The tests were carried out considering the temperatures of the air and of the pavement. The new measurement protocol adopted established that during a single session the vehicles (Vehicle 1 and Vehicle 2) used like reference passes on the lane close to the accelerometer at different speeds. These condition allow to the operator working at the roadside to record several steps, in order to mediate in a post-processing analysis the different conditions of transit and interaction tyre/surface. The same pattern was applied to both pavements.
During the phase of post-processing it has been analyzed the accelerometric signal of each passage, choosing appropriate frequency bands used to evaluate the energy content. The frequency bands have been chosen in function of the energy content of the signal analyzed in narrowband, and respect to what reported in the literature.

Figure 17 Placements of an accelerometer

The frequency bands chosen for the analysis of the accelerometric signals are reported in the following Table 7. The first band can be considered a broad band, including the top 5 narrow bands used.

Table 7 Frequency bands considered for the analysis

Index	1	2	3	4	5	6	7	8
Band [Hz]	8 ÷ 1500	10 ÷ 100	100 ÷ 200	200 ÷ 400	400 ÷ 800	800 ÷ 1500	1500 ÷ 2000	2000÷ 3000

The band between 10 Hz and 100 Hz is the bandwidth more interesting from the structural point of view for the pavement vibrations, because it can be influenced by the materials used. The two successive bands are equally important, in fact according to the standard (UNI 9916: 2004) the upper limit of the frequency range affected by the vibrations from road traffic is 300 Hz. The increase of the frequency is caused by phenomena due to the macro-texture of the pavement and by the internal structure.
For each band, it was estimated the total energy of a single event (SEL_A). that is calculated in a similar way to the case of acoustic phenomena.
Then it has been calculated the average of the values in SEL_A obtained for each event for each band, and the dispersion around the peak represents the variability of the phenomenon.
All the results are reported in the following Figures 18 to 21:

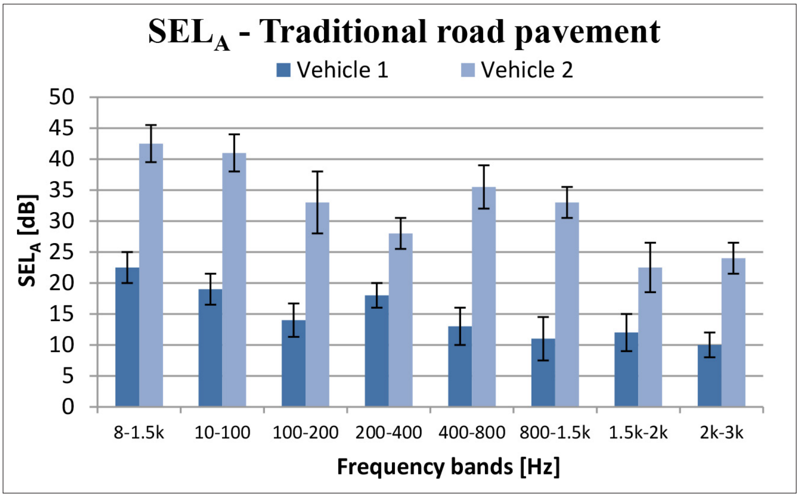

Figure 18 Comparison between the SEL_A obtained for the traditional pavement for both vehicles

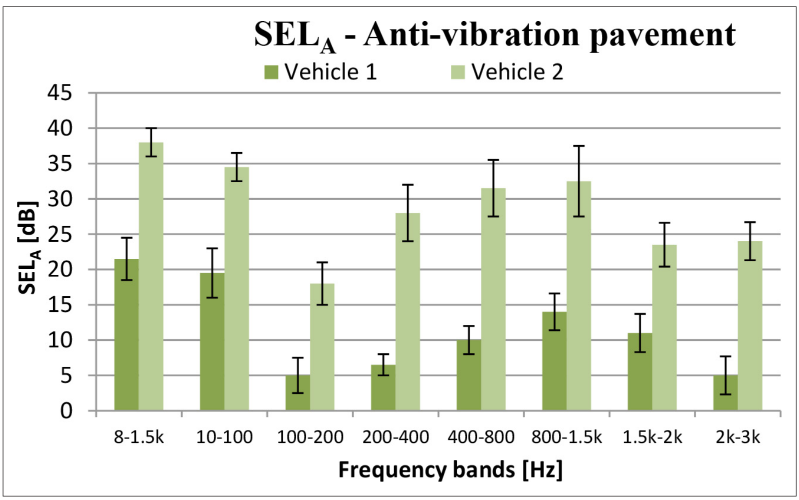

Figure 19 Comparison between the SEL_A obtained for the anti-vibration pavement for both vehicles

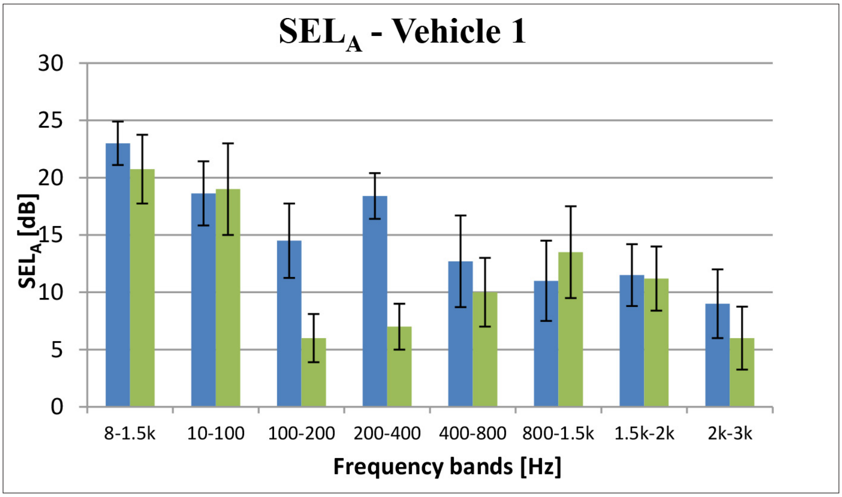

Figure 20 Comparison between the SEL_A obtained for the Anti-vibration and Traditional pavement for vehicle 1

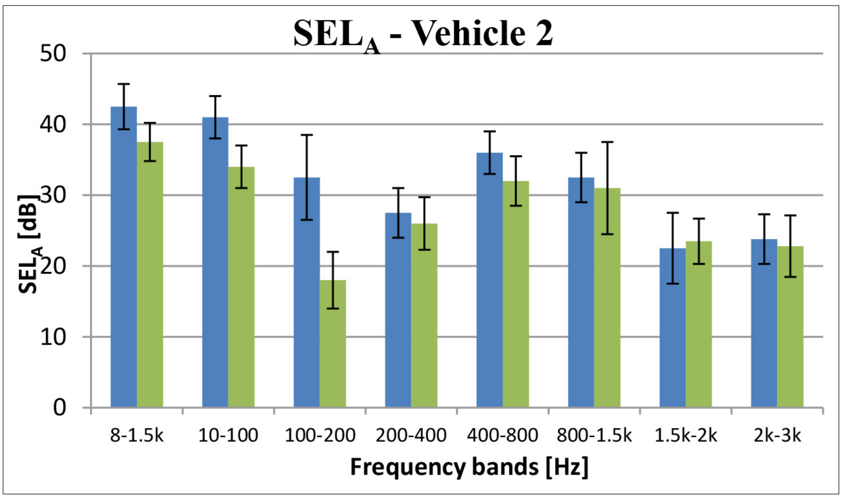

Figure 21 Comparison between the SEL_A obtained for the Anti-vibration and Traditional pavement for vehicle 2

The uncertainties associated to the values are big due to the few number of steps, that caused an increase of dispersion of the results. The Figures 20 and 21 show for each vehicle, the comparison of the SEL_A results, between the special pavement and the reference one. After the analysis of the results, some considerations about the relationship between the two pavements investigated can be done:

- for the band 10-100 Hz and for the SEL_A, the two asphalt pavement have the same behavior considering the Vehicle 1, while with the Vehicle 2 the pavement used as reference has shown lower values in comparison to the pavement with polymeric compound, in fact the difference is about – 6.6±3.5 dB;
- for the band 100-200 Hz the pavement with compound has a lower values in comparison with the reference one for both vehicles;
- for the band 200-400 Hz the pavement with the compound has a lower values;

• all bands which cover the frequency ranges higher than 400 Hz have values not so different between the two pavements, using both parameters for both vehicles.

The final difference between the normal wearing course and the use of a no-noise technology is reported in the following Table 8:

Table 8 Difference between the normal wearing course and the no-noise layer using different vehicles

Band [Hz]	8 ÷ 1500
Vehicle 1 [dB]	-1.7 ± 3.7
Vehicle 2 [dB]	-4.9 ± 3.8

Using this compound made with rubber powder and different polymers it has been possible to reduce the SEL_A in an average quantity of about 2 – 5 dB in function of the vehicle used.

7 Conclusions

As result of different years of research, the compound contained rubber powder can reduce the noise and the vibration caused by vehicles. Using the road with the modified wearing course, the users perceive this advantage. In fact the anti-vibration component can be seen as direct benefit, but also the noise reduction like indirect benefit. In collaboration with ARPA Piemonte and iPOOL, a spin-off of the Italian National Research Council (CNR), the tests made on the pavement in Alessandria and in Novara have confirmed in objective way the anti-vibration and noise reduction performance. Thanks to a spotted sessions of measurement it's possible to evaluate the influence of different parameters used. Furthermore it's possible to evaluate accurately the effect of the studied mix design and the use of rubber powder on the vibration and noise behavior of the pavement.
The results after different analysis show how it's possible to reduce traffic noise and vibration starting from the asphalt mix project, because we can act on different parameters that can act simultaneously on the noise emission.

References

[1] Rumore e Vibrazioni da Traffico – l'Influenza delle Caratteristiche Superficiali delle Pavimentazioni, Associazione Mondiale della Strada – AIPCR – Comitato Nazionale Italiano, 1998;

[2] Donati, P.M.: Joel's Breaker: forty year of European Vibration Prevention, Institut National de Recherche et de Securitè, Vandoeuvre Les Nancy, France, – Industrial Helth 2012, 50, 370-376;

[3] Grandi, F.: La progettazione di pavimentazioni antivibranti, Tesi di Dottorato, 2008;

[4] Formela, K., Haponiuk, J.: Characterization and Properties of LDPE/(Ground TyreRubber)/Crosslinked Butyl Rubber Blends, Journal of Vinyl and Additive Technology;

[5] Chetoni, M., Teti, L., Bianco, F.: Misure di vibrazione da traffico stradale, iPOOL srl, 2015;

[6] Indagine sperimentale delle proprietà meccaniche e funzionali di strati di usura "dense – graded" ad emissione acustica ottimizzata per la riduzione del rumore stradale, Tesi di laurea di S. Carrara, 2013;

[7] Holubka M., Salaiova B.: The use of crushed rubber in asphalt mixtures of road pavements, Civil Engineering Faculty, Technical University of Košice, Slovakia, 2013;

[8] Coni, M., Silanos, G., Annunziata, F.: Le vibrazioni indotte dalle irregolarità superficiali del profilo stradale, Dipartimento di Ingegneria del Territorio, Università di Cagliari – Convegno Nazionale, Traffico e Ambiente Trento, 21-25 febbraio 2000;

[9] Thomas, F.: "Suoni variabili nel tempo, attenuazioni del livello sonoro", Lezione XXXIII (disponibile sul web);

[10] Ferro, R.: Vibrazioni da traffico stradale: caratterizzazione dello spettro di carico, trasmissione alle strutture e valutazione degli effetti dinamici conseguenti, Tesi di Laurea, Università degli studi di Firenze, 1997.

[11] Carrara, S.: Indagine sperimentale delle proprietà meccaniche e funzionali di strati di usura "dense – graded" ad emissione acustica ottimizzata per la riduzione del rumore stradale, Tesi di Laurea, Politecnico di Milano, 2013.