In situ measurements of the intrinsic characteristics of the acoustic barriers installed along a new high speed railway line[a)]

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In September 2005 the new high speed railway line Torino-Novara, Italy, was near completion and acoustic barriers had just been installed according to specifications. At this site, the authors conducted in situ verification of the intrinsic characteristics of the noise reducing devices. It is the first European experience of this kind on a large construction workplace. The conditions were extremely demanding and the time scheduled for the task very short. The challenging task was successfully completed applying CEN/TS 1793-5 and taking advantage of the logistic support of the customer. The paper reports the key points of this successful experience and shows some exemplary results. The values measured in situ are compared with the results obtained some years before on products of the same kind. Regarding sound reflection, the in situ method proved to be reliable and to give values more realistic than the laboratory method. Regarding sound insulation, the comparison with previous measurements indicates that, as long as the barriers are well installed, similar results can be expected and that their variance is comparable to that of laboratory tests. On the other hand, large differences (4−5 dB or more) indicate poor quality of construction and installation work, that can be confirmed by a careful inspection. This sensitivity of the in situ method to detect faults paves the way to establish minimum construction and installation criteria. It is concluded that the selected method is fully adequate to in situ verification and could be repeatedly applied to check the acoustic durability of noise reducing devices over time.

Primary subject classification: 31.1; Secondary subject classification: 72.9

1 INTRODUCTION

The new high speed railway line Torino-Novara, Italy, was opened in February 2006. About 100,000 m^2 of acoustic barriers have been installed along the 86 km of the line to protect the environment from the noise emitted by high speed trains. There are four main types of noise barriers: metallic cassettes filled with glass wool, timber and metal cassettes filled with glass wool, concrete panels with a porous side and acrylic sheets plus smooth concrete panels (see Fig. 1 and Table 1). All of them are constructed in a similar way: acoustic panels supported by steel beams (HE 160 type) which are clamped to a reinforced concrete sustaining wall. The barrier height ranges from 3 m to 5.5 m.

In September 2005 the noise screens were almost all installed and the authors were asked to verify their acoustic intrinsic characteristics in situ[1]: this means the sound absorption (or reflection) and the airborne sound insulation, which in European standards are called *intrinsic* characteristics because they depend only on the device under test and not on the environment in which it is installed. The intrinsic characteristics are different from the insertion loss, which depends also on the environment and on the relative source, receiver and screen positions.

The task was very demanding; in fact, it was requested to carry out the measurements:

1. according to high quality technical standards;
2. on site during the final phase of the construction work;

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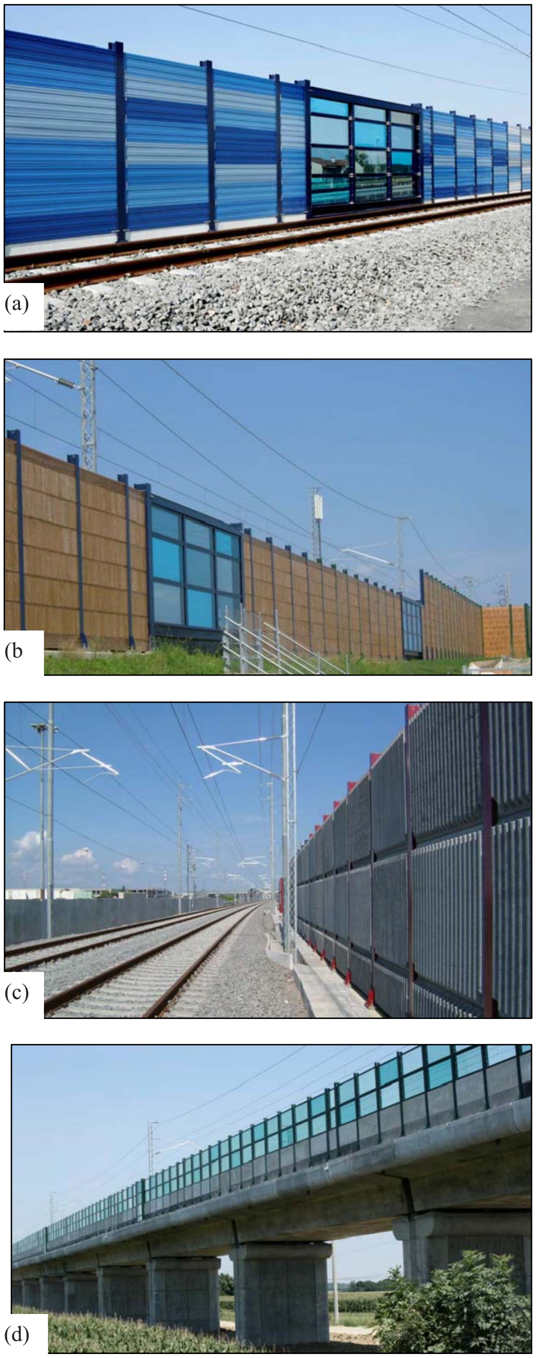

Fig. 1—Main types of noise barriers installed: (a) metallic cassettes filled with glass wool; (b) timber and metal cassettes filled with glass wool; (c) concrete panels with a porous side; (d) acrylic sheets and smooth concrete panels.

3. beginning just after the signature of the contract and ending in seven days;
4. working only during selected time slots (Saturday, Sunday, overnight after 22:00 hours); for the rest of the time a special test train was active on the line.

Table 1—Types of acoustic barriers installed along the Torino-Novara railway line.

Barrier type	Installed quantity
Metallic cassettes filled with glass wool	25 000 m^2
Timber and metal cassettes filled with glass wool	25 000 m^2
Concrete panels with a porous side	30 000 m^2
Acrylic sheets and concrete panels (reflective)	15 000 m^2
Others	5 000 m^2

The authors decided to accept the challenge with some further specifications:

• in order to fulfil requirements 1 and 2 above, the measurement method shall conform to the European technical specification CEN/TS 1793-5[2], the sole technical guideline applicable on site (of course the customary laboratory procedures are not applicable on site);

• in order to limit the amount of work (see requirement 3 above), the test shall be applied to sample sections of the four main types of noise barriers, with a random selection for each of them;

• in order to fulfil requirements 3 and 4 above, the customer shall give the logistic support to quickly move inside and outside the railway line, to provide light spots during the nights, etc.

The present work is the first European experience of this kind on a large construction workplace. Previously published applications of the selected method were done in the framework of the Adrienne project[3,4], as preliminary tests for selecting the barriers to be installed along some parts of the new high speed railways in Italy[5,6] and for a research on the timber barrier types largely used in the United Kingdom[7]. In particular the many data reported in Refs. 5 and 6 pertains to panels almost identical to those tested in situ alongside the high speed railway (same design, same materials, same manufacturers); this gives the opportunity to compare the values of sound reflection and insulation measured in situ with the results obtained some years before on similar products and thus to check the reliability of the measurement method and to get some indications on its reproducibility.

2 SUITABILITY OF THE PROCEDURE

The equipment, conforming to CEN/TS 1793-5[2], proved to be easy to move inside the railway line. The logistic support of the customer was of great help to respect the tight time schedule: it was also possible to place the equipment close to barrier sections that were

Fig. 2—Placing the microphone grid for airborne sound insulation measurements outside a viaduct.

difficult to reach and that usually are never tested (see Fig. 2).

For the sound reflection index (*RI*) measurements the usual in situ procedure[2] was applied without modifications. For the sound insulation index (*SI*) measurements, according to CEN/TS 1793-5 the in situ value, in each frequency band, should be obtained by averaging the values subsequently measured at nine points in front of the sample under test by moving the same microphone (see Sec. 3 for a summary of the procedure). Due to the short time available for the measurements, it was decided to work with a 9-microphone grid in place of a single microphone (see Fig. 3).

3 PRINCIPLE OF MEASUREMENT

Here the principle of measurement is only briefly recalled in order to improve the readability of what follows; for further details the reader is referred to CEN/TS 1793-5[2].

3.1 Sound Reflection

A loudspeaker-microphone assembly is located so that the microphone is in a *reference position* in front of

Fig. 3—Airborne sound insulation measurements: the microphone grid and the sound source in place for the acrylic barrier on the viaduct of Fig. 2.

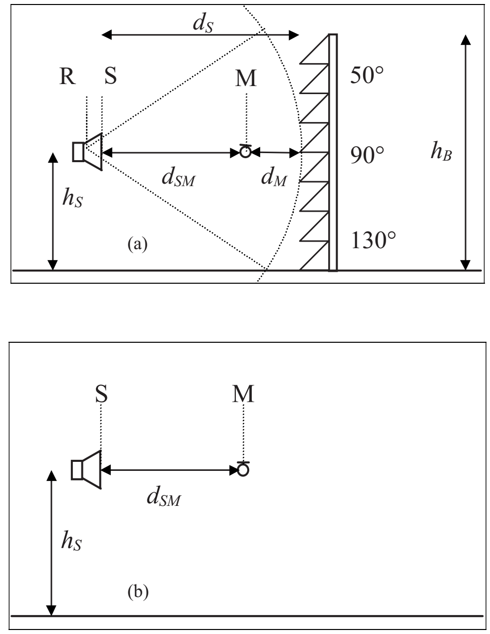

Fig. 4—Sketch of the set-up for the reflection index measurement (example for rotation in vertical direction)—R: axis of rotation—S: loudspeaker front panel—M: microphone. (a) reflected sound measurements, from 50° to 130° in step of 10° on the same rotation plane, in front of a non flat noise reducing device; (b): reference "free-field" sound measurement.

the device under test (see Ref. 2). The distance of the microphone from the loudspeaker must be kept strictly constant. This can be done using a proper loudspeaker-microphone assembly. Around the reference position, a set of nine measurement positions, including the reference position, are defined and reached by rotation of the loudspeaker-microphone assembly, around the axis of rotation, on the same plane in steps of 10° (Fig. 4(a)).

In each position, the sound source emits a transient sound wave that travels past the microphone position to the device under test and is then reflected from it. The microphone placed between the sound source and the device under test receives both the direct sound pressure wave travelling from the sound source to the device under test and the sound pressure wave reflected (including scattering) by the device under test. If the measurement is repeated without the device under test in front of the loudspeaker-microphone assembly, the direct free-field wave can be acquired. The power spectra of the direct and the reflected components, corrected to take into account the path length difference of the two components, gives the basis for calculating the reflection index *RI*. Other reflections, such as diffracted waves from the upper edge of the device under test, are separated from reflected waves by the time windowing procedure specified in CEN/TS 1793-5[2].

The measurement must take place in an essentially free field in the direct surroundings of the device, i.e. a field free from reflections coming from surfaces other than the surface of the device under test. For this reason, the acquisition of an impulse response having peaks as sharp as possible is recommended: in this way, the reflections coming from surfaces other than the tested device can be identified from their delay time and rejected by proper time windowing. The "Adrienne" temporal window has been used, according to the reference standard[2]; for further information on this window the reader is referred to Refs. 3–6.

The expression used to compute the reflection index, *RI*, as a function of frequency, in one-third octave bands, is:

$$RI_j = \frac{1}{n_j} \sum_{k=1}^{n_j} \frac{\int_{\Delta f_j} |F[t \cdot h_{r,k}(t) \cdot w_r(t)]|^2 df}{\int_{\Delta f_j} |F[t \cdot h_i(t) \cdot w_i(t)]|^2 df} \tag{1}$$

Where:

- $h_i(t)$: is the incident reference component of the free-field impulse response;
- $h_{rk}(t)$: is the reflected component of the impulse response at the k-th angle;
- $w_i(t)$: is the incident reference free-field component time window (Adrienne temporal window[2]);
- $w_r(t)$: is the reflected component time window (Adrienne temporal window[2]);
- F: is the symbol of the Fourier transform;
- j: is the index of the one-third octave frequency bands (between 100 Hz and 5 kHz);
- Δf_j: is the width of the j-th one-third octave frequency band;
- n_j: is the number of angles on which to average ($n \leqslant 9$ per rotation, see Ref. 2);
- t: is a time whose origin is at the beginning of the impulse response acquired by the measurement chain.

It is worth noting that the reflections from different portions of the surface under test arrive at the microphone position at different times, depending on the travel path from the loudspeaker to the position of each test surface portion and back. The longer the travel path from the loudspeaker to a specific test surface portion and back, the greater the time delay. Thus, the amplitude of the reflected sound waves from different test surface portions, as detected at the microphone position, is attenuated in a manner proportional to the travel time. In order to compensate for this effect, t is included as a factor in both numerator and denominator in Eqn. (1).

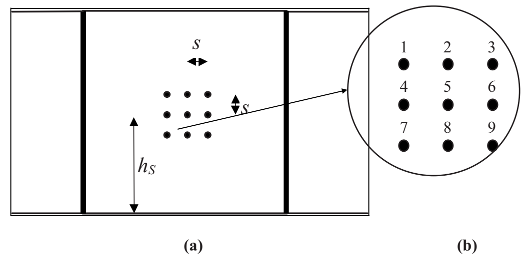

Fig. 5—(not to scale) (a) measurement grid for sound insulation index measurements (front view, receiver side); (b) numbering of the measurement points.

3.2 Airborne Sound Insulation

A vertical measurement grid constituted of nine equally spaced points is defined. This measurement grid is square, with a side length $2 \cdot s$ equal to 0,80 m. Its center was located at a height equal to half the height of the noise reducing device under test. The grid was placed facing the side of the noise reducing device under test opposite to the side to be exposed to noise when the device is in place, so that its horizontal distance to the closest point of the device was 0.25 m (see Fig. 5). The grid was placed at a distance as large as possible from the lateral edges of the noise reducing device under test.

The sound source emitted a transient sound wave that travelled toward the device under test and was partly reflected, partly transmitted and partly diffracted by it (Fig. 6(a)). The microphone placed on the other side of the device under test received both the transmitted sound pressure wave travelling from the sound source through the device under test, and the sound pressure wave diffracted by the top edge of the device under test (for the test to be meaningful the diffraction from the lateral edges should be sufficiently weak and delayed). If the measurement is repeated without the device under test between the loudspeaker and the microphone, the direct free-field wave can be acquired (Fig. 6(b)). The power spectra of the direct wave and the transmitted wave, corrected to take into account the path length difference of the two waves, gives the basis for calculating the sound insulation index. The final sound insulation index is the logarithmic average of the sound insulation indices measured at nine points placed on the measurement grid (Fig. 5).

The measurement took place in a sound field free from reflections within the analysis window. For this

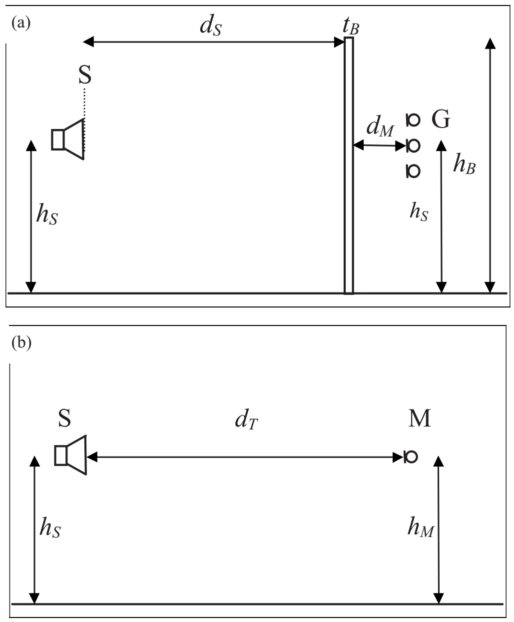

Fig. 6—Sketch of the set-up for the sound insulation index measurement—Normal incidence of sound on the sample—S: loudspeaker front panel—G: measurement grid—M: microphone—(a) transmitted components measurement in front of a flat noise reducing device; (b) free-field (incident) component measurement –($d_T = d_S + t_B + d_B$).

reason, the acquisition of an impulse response having peaks as sharp as possible was used. In this way, the reflections coming from other surfaces could be identified from their delay time and rejected.

The expression used to compute the sound insulation index SI as a function of frequency, in one-third octave bands, is:

$$SI_j = -10 \cdot \lg \left\{ \frac{\sum_{k=1}^{n} \int_{\Delta f_j} |F[h_{tk}(t) w_{tk}(t)]|^2 df \left(\frac{d_k}{d_i} \right)^2}{n \cdot \int_{\Delta f_j} |F[h_i(t) w_i(t)]|^2 df} \right\} \tag{2}$$

where

- $h_i(t)$: is the incident reference component of the free-field impulse response;
- $h_{t,k}(t)$: is the transmitted component of the impulse response at the k-th scanning point;
- d_i: is the geometrical spreading correction factor for the reference free-field component;
- d_k: is the geometrical spreading correction factor for the transmitted component at the k-th scanning point ($k=1,\ldots,n$);
- $w_i(t)$: is the reference free-field component time window (Adrienne temporal window[2]);
- $w_{tk}(t)$: is the time window (Adrienne temporal window[2]) for the transmitted component at the k-th scanning point;
- F: is the symbol of the Fourier transform;
- j: is the index of the j-the one-third octave frequency bands (between 100 Hz and 5 kHz);
- Δf_i: is the width of the j-the one-third octave frequency band;
- $n=9$: is the number of scanning points.

d_i and d_k are geometrical spreading correction factors, computed using geometry and taking into account the barrier thickness and the measurement grid step (0.40 m), see Ref. 2.

For SI measurements on noise reducing devices having intermediate posts, like acoustic barriers constituted by one or several acoustic elements sustained by vertical posts at fixed distances, a set of nine measurements on the measurement grid plus a free-field measurement must be performed both in the middle of a representative element, and in front of a representative post. In this way, two SI values result for each test section.

3.3 Single Number Ratings

A single number rating for each intrinsic characteristic (RI and SI) was derived to indicate the performance of the product[2]. The individual frequency-dependent values were weighted according to the normalized traffic noise spectrum defined in EN 1793-3[8].

The single number rating of sound reflection DL_{RI}, in decibel, is given by:

$$DL_{RI} = -10 \cdot \lg \left[\frac{\sum_{i=m}^{18} RI_i \cdot 10^{0,1 L_i}}{\sum_{i=m}^{18} 10^{0,1 L_i}} \right] \tag{3}$$

Where:

- $m=4$: (number of the 200 Hz one-third octave frequency band);
- L_i: relative A-weighted sound pressure levels (dB) of the normalized traffic noise spectrum, as defined in EN 1793-3, in the i-th one-third octave band.

Regarding airborne sound insulation, two single number ratings were derived to indicate the performance of the product: one for the measurement in front of the acoustic elements and the other for the measurement in front of a post (if applicable). The individual sound insulation index values coming from element scanning and post scanning were weighted according to

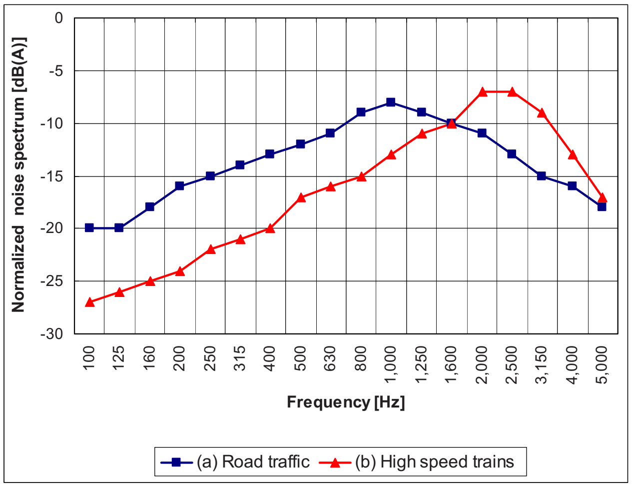

Fig. 7—Reference noise spectra for: (a) road traffic, according to EN 1793-3; (b) high speed railway traffic, according to UNI 11160.

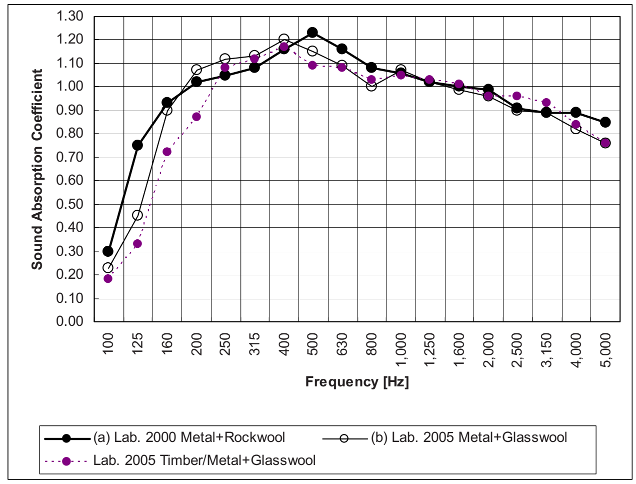

Fig. 8—Sound absorption coefficients measured in the laboratory. (a) metallic cassettes filled with rock wool, measured in 2000; (b) metallic cassettes filled with glass wool, measured in 2005; (c) mixed timber/metal cassettes filled with glass wool, measured in 2005.

the normalized traffic noise spectrum defined in EN 1793-3[8]. The single number rating of airborne sound insulation DL_{SI}, in decibel, is given by:

$$DL_{SI} = -10 \cdot \lg\left[\frac{\sum_{i=m}^{18} 10^{0,1L_i} 10^{-0,1SI_i}}{\sum_{i=m}^{18} 10^{0,1L_i}}\right] \qquad (4)$$

Where:

$m=4$: (number of the 200 Hz one-third octave frequency band);

L_i: relative A-weighted sound pressure levels (dB) of the normalized traffic noise spectrum, as defined in EN 1793-3, in the i-th one-third octave band.

Both above-mentioned single number ratings are reported after having being rounded to the nearest integer.

It is worth noting that the normalized noise spectrum defined in EN 1793-3 refers to road traffic, because the standard was developed for noise reducing devices to be installed along roads, while the present application refers to a railway line. This was not be a problem, because the full information is given by the spectrum of the observed quantity (*RI* and *SI*) and its single number rating is simply a tool for ranking the products. It is clear that different spectra, weighting the various frequency bands differently can change the ranking. Therefore in the following discussion the single number rating values will be calculated both using the reference road traffic spectrum taken from EN 1793-3[8] and the reference high speed train spectrum taken from the Italian standard UNI 11160[9]. The two spectra are compared in Fig. 7: both are normalized to an overall value of 0 dB because their absolute value is not important; instead, their shape is important. It can be seen that the high speed train spectrum weighting is higher in the 2 kHz−4 kHz frequency range compared to the road traffic spectrum.

4 VERIFICATION OF SOUND ABSORPTION

4.1 Metallic Cassettes Barriers

Figure 8 shows the Sabine's sound absorption coefficient, α_S, measured in the laboratory, obtained during the 2005 measurement campaign (curve (a)) compared with the similar curve obtained for cassettes of the same kind from the same manufacturer in 2000 (curve (b)).

Figure 9 shows the curves of the Sabine's reflection coefficient, r_S, obtained from the Sabine's sound absorption coefficient α_S, and of the reflection index *RI*, measured in situ during the 2005 measurement campaign, compared with the similar curves obtained for cassettes of the same kind from the same manufacturer in 2000. The reflection coefficient in the laboratory, r_S, has been obtained from the Sabine's sound absorption coefficient α_S, which is the quantity actually measured in the laboratory. When, as a result of the Sabine's approximations, α_S has values exceeding 1, r_S has been set to zero:

$$\begin{cases} r_S = 1-\alpha_S, \alpha_S \leqslant 1 \\ r_S = 0, \alpha_S > 1 \end{cases} \qquad (5)$$

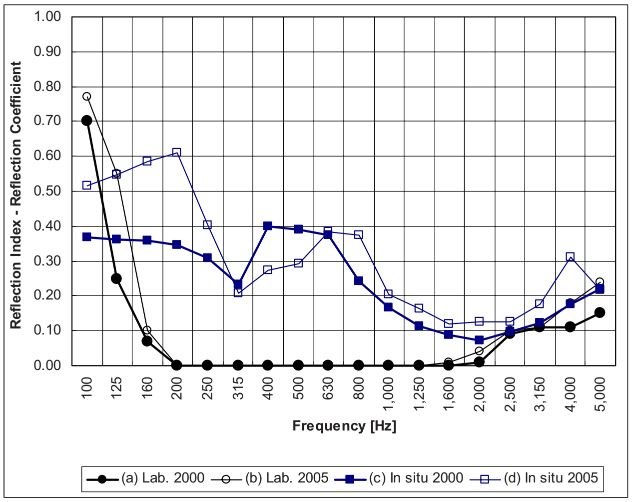

Fig. 9—Reflection coefficient (in the laboratory) and reflection index (in situ) of the metallic cassettes filled with mineral wool barrier type. (a) in the laboratory, filled with rock wool; (b) in the laboratory, filled with glass wool; (c) in situ, filled with rock wool; (d) in situ, filled with glass wool.

As discussed elsewhere[3–5], the in situ results are different from the laboratory results because of the differences in the test sound fields (diffuse in the laboratory, directional in situ), in the definition of the relevant quantity (the *reflection index* should not be confused with the reflection coefficient) and of the post processing methods used.

The metallic cassettes are identical except that in the year 2005 they were filled with glass wool while in the year 2000 they were filled with rock wool. As can be seen, the laboratory curves, measured in a reverberation room according to EN 1793-1[10], are very similar and have the same single number rating: 20 dB (maximum allowable). The two curves measured in situ with a 5-year time interval show a reasonable resemblance above the 250 Hz 1/3 octave band and get a 1 dB difference between their single number ratings (Table 2):

- using the road traffic spectrum, 7 dB rock wool (2000) and 6 dB glass wool (2005);
- using the high speed train spectrum, 9 dB rock wool (2000) and 8 dB glass wool (2005).

It is worth noting that the laboratory method gives to all strongly absorptive products the same rating (20 dB), while the in situ method yields more realistic values. In fact, in EN 1793-1[10], Annex B, it is written that the single number rating DL_α is "most directly relevant to characterizing absorptive performance in situations where sound radiating from the traffic stream is reflected from the absorptive surface and travels directly to the receiver position…." It is evident that an attenuation of 20 dB is excessively optimistic, while the values obtained on site are more plausible.

4.2 Mixed Barriers in Timber and Metal

About 25% of the installed barriers are composed of "mixed" cassettes in timber and metal filled with glass wool. The cassette side facing the noise source is made with perforated sheet-aluminium, while the rear side facing the environment is made with larch timber; both sides are fixed to two horizontal wooden beams.

Figure 8 shows the Sabine's sound absorption coefficient, α_S, measured in the laboratory according to EN 1793-1[10], obtained during the 2005 measurement campaign (curve (c)). Figure 10 shows the curve of the reflection coefficient r_S, obtained applying Eqn. (5) to the values of α_S, and the reflection index, measured in situ, for the timber/metal cassettes compared with the corresponding curves for the "full metal" cassettes. The laboratory curves are very similar and have the same single number rating: 20 dB (maximum allowable).

Table 2—Single number ratings of the sound absorption coefficient (in the laboratory) and the sound reflection index (in situ) for some selected test sections.

Barrier type	Road traffic spectrum		High speed train spectrum	
	DL_α [dB] Laboratory	DL_{RI} [dB] In situ	DL_α [dB] Laboratory	DL_{RI} [dB] In situ
Metallic cassettes filled with rock wool (2000)	20	7	20	9
Metallic cassettes filled with glass wool (2005)	20	6	20	8
Timber/Metal cassettes filled with glass wool (2005)	20	5	20	7
Concrete panels with a porous side (2001)	5	1	7	3
Concrete panels with a porous side (2005)	—	2	—	3
Framed acrylic sheets (1999)	0	0	0	1
Framed acrylic sheets and concrete panels (2005)	—	−1	—	0

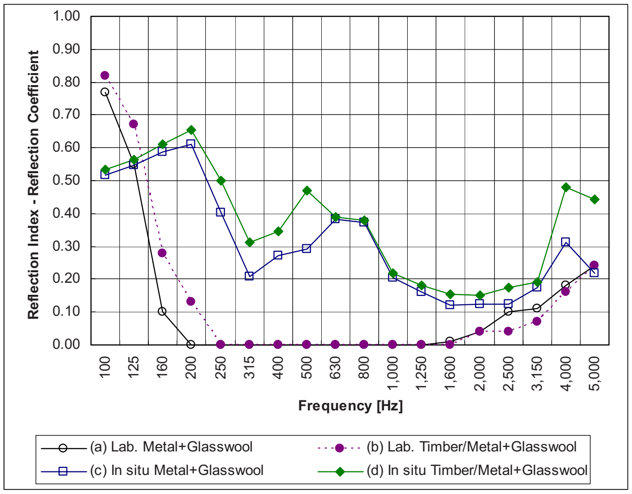

Fig. 10—Reflection coefficient (in the laboratory) and reflection index (in situ) of the metallic cassettes and mixed timber/metal cassettes filled with mineral wool barrier type. (a) in the laboratory, full metal; (b) in the laboratory, mixed timber/metal; (c) in situ, full metal; (d) in situ, mixed timber/metal.

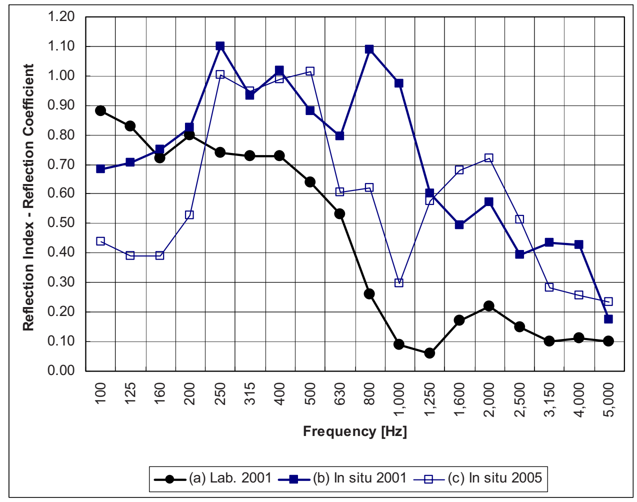

Fig. 11—Reflection coefficient (in the laboratory) and reflection index (in situ) of the concrete panels barrier type. (a) in the laboratory, measured in 2001; (b) in situ, measured in 2001; (c) in situ, measured in 2005.

The two curves measured in situ show a reasonable resemblance and get the following single number ratings (Table 2):

- using the road traffic spectrum, 5 dB metal/timber and 6 dB full metal;
- using the high speed train spectrum, 7 dB metal/timber and 8 dB full metal.

4.3 Concrete Barriers

About 30% of the installed barriers are composed of massive concrete panels. The side facing the noise source is made of porous concrete, partly sound absorbing.

Figure 11 shows the curves of the Sabine's reflection coefficient (measured in the laboratory according to EN 1793-1[10]) and the reflection index (measured in situ) obtained from a test in 2001 compared with the reflection index (measured in situ) obtained during the 2005 measurement campaign. In both cases the products come from the same manufacturer. The laboratory curve gets the single number rating of 5 dB with the road traffic spectrum and of 7 dB with the high speed train spectrum. The two curves measured in situ with a 4-year time interval show a reasonable resemblance except in the 800 Hz–1600 Hz 1/3 octave bands: this may be due to the variability in manufacturing concrete products (for example, the porosity of the surface layer is difficult to keep constant in large scale production). The two curves have the following single number ratings (Table 2):

- using the road traffic spectrum, 1 dB in 2001 and 2 dB in 2005;
- using the high speed train spectrum, 3 dB in 2001 and 3 dB in 2005.

There is a 1 dB difference when using the road traffic spectrum, but no difference when using the high speed train spectrum: in fact the latter is dominated by the 2 kHz–4 kHz frequency range values (Fig. 7), which for the two measured *RI* curves compensate each other.

4.4 Acrylic and Concrete Barriers

About 15% of the installed barriers are composed of acrylic sheets inserted into a metallic frame and supported by reflective concrete panels 1 m high. These are strongly reflective products and an absorption/reflection test is not interesting, but some measurements were requested for compliance with specifications, even if it is clear that the result is dominated by the sharp reflections coming from the sharp metallic frame supporting the acrylic sheets and the resonance modes of the acrylic sheets. Figure 12 shows the reflection curves measured in 1999, both in the laboratory and in situ, for a similar transparent barrier and those measured in situ in 2005 for the installed device. While the laboratory curve is almost flat and yields a single number rating of 0 dB, as expected for a fully reflective sample, the in situ curves are influenced by the shape of the frame; the 2005

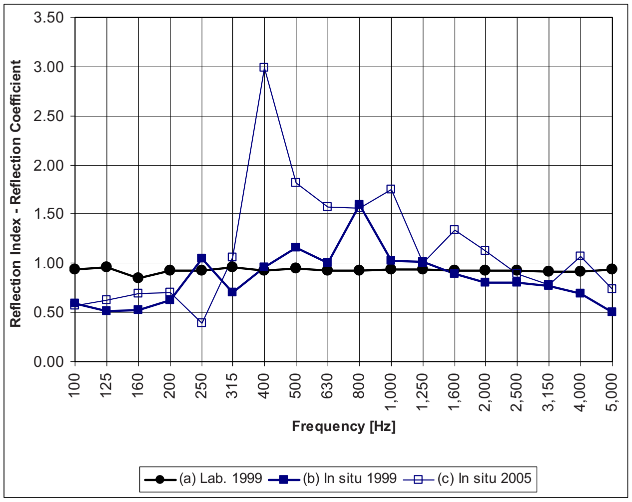

Fig. 12—Reflection coefficient (in the laboratory) and reflection index (in situ) of the acrylic panels barrier type. (a) in the laboratory, measured in 1999; (b) in situ, measured in 1999; (c) in situ, measured in 2005.

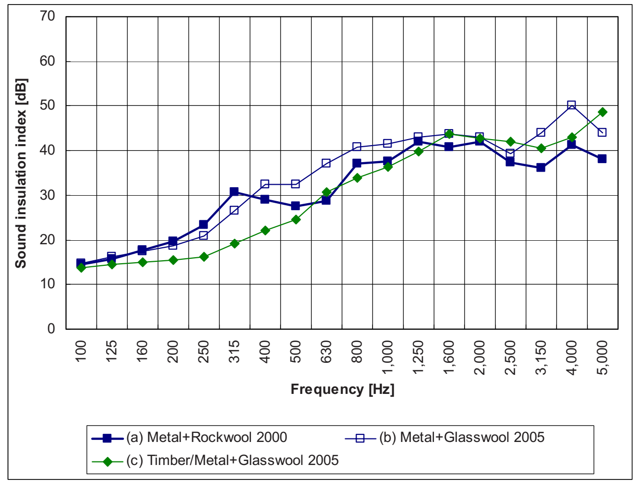

Fig. 13—Sound insulation index measured in situ in front of three types of cassettes: (a) full metal filled with rock wool, measured in the year 2000; (b) full metal filled with glass wool, measured in the year 2005; (c) mixed timber/metal filled with glass wool, measured in the year 2005.

measurement exhibits a pronounced peak in the 400 Hz band. The fluctuations are due to the reflections from the sharp edges of the supporting metallic structure (passing through the measurement area, see Figures 2 and 3) and to the resonance modes of the acrylic sheets when exposed to a direct sound field on site. The single number rating for in situ results are: 0 dB (road traffic spectrum) or 1 dB (high speed railway spectrum) for the 1999 curve (both spectra) and −1 dB (road traffic spectrum) or 0 dB (high speed railway spectrum) for the 2005 curve. The negative value of the single number rating obtained in situ in 2005 (road traffic spectrum) can be understood comparing Eqn. (3) with the analogous formula used for the laboratory results in EN 1793-1[10]:

$$DL_{\alpha} = -10 \cdot \lg\left[1 - \frac{\sum_{i=1}^{18} \alpha_{Si} \cdot 10^{0,1L_i}}{\sum_{i=1}^{18} 10^{0,1L_i}}\right] \qquad (6)$$

As numeric fluctuations in the second term inside brackets in Eqn. (6) can give rise to abnormally high values of the single number rating, in the laboratory standard EN 1793-1[10] it is specified that its values are limited to be $\leqslant 0.99$ (corresponding to $DL_{\alpha}=20$ dB); thus DL_{α} can have values ranging from 0 dB to 20 dB. In a similar way, as numeric fluctuations in the term inside brackets in Eqn. (3) can give rise to abnormal values of the single number rating, in CEN/TS 1793-5[2] it should be specified that the values of this term are limited to be $\leqslant 0.99$ (corresponding to $DL_{RI}=0$ dB) and to be $\geqslant 0.01$ (corresponding to $DL_{RI}=20$ dB). With this additional specification, the single number rating for the 2005 acrylic sample would be $DL_{RI}=0$ dB, eliminating the negative value. It is hoped that this suggestion will be taken into account in the next revision of CEN/TS 1793-5.

5 VERIFICATION OF SOUND INSULATION

In this section the in situ results are compared with laboratory results obtained using two coupled reverberation rooms, as detailed in EN 1793-2[11].

5.1 Metallic Cassettes Barriers

According to CEN/TS 1793-5, the in situ measurements of the sound insulation index must be repeated in front of the acoustic elements and in front of a post. Figure 13 shows the sound insulation index curves measured in front of the cassettes (the “acoustic elements”) with a 5-year time interval; Figure 14 shows the sound insulation index curves measured in front of a post. Table 3 reports the single number ratings. It can be seen that for manufacturer B:

- in the laboratory, the difference between the two single number ratings is 1 dB using the road traffic spectrum (24 dB vs. 25 dB) and 2 dB using the high speed train spectrum (28 dB vs. 30 dB);
- in situ in front of the acoustic elements, the difference between the two single number ratings is 0 dB using the road traffic spectrum (31 dB

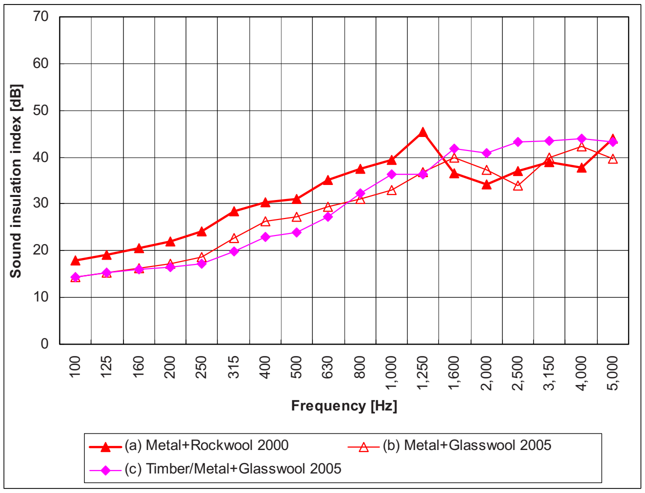

Fig. 14—Sound insulation index measured in situ in front of a post where the junction between acoustic and structural elements has a great influence: (a) full metal filled with rock wool, measured in the year 2000; (b) full metal filled with glass wool, measured in the year 2005; (c) mixed timber/metal filled with glass wool, measured in the year 2005.

for both) and 2 dB using the high speed train spectrum (35 dB vs. 37 dB);

- in situ in front of a post, the difference between the two single number ratings is −4 dB using the road traffic spectrum (32 dB vs. 28 dB) and −2 dB using the high speed train spectrum (35 dB vs. 33 dB).

For the measurements in the laboratory and in front of the acoustic elements, the values of the single number rating obtained in 2005 are equal or larger than those obtained in 2000, with a maximum difference of 2 dB. This is what is commonly expected from the combined effects of the measurement uncertainty and variance in workmanship. The measurements in front of a post show an opposite trend: the values obtained in 2005 are smaller than those obtained in 2000, with a maximum difference of −4 dB when using the road traffic spectrum. Also, Fig. 14 shows that there is a clear shift between the two curves of sound insulation index in the 1/3 octave bands from 100 Hz to 1250 Hz. This effect could be due to a poor sealing at the junction between panels and posts, which is difficult to quantify if it is due to poor workmanship or non optimal gaskets.

Figure 15 shows the results obtained in situ for a different test section (called here section B, whereas the previous data refer to section A), where the cassettes, made by another manufacturer (called here manufacturer B, where as the previous manufacturer will be named manufacturer A), have a different, more accurate, design at the junction. The comparison

Table 3—Single number ratings of the airborne sound insulation (in the laboratory) and the sound insulation index (in situ) for some selected test sections.

Barrier type	Road traffic spectrum			High speed train spectrum		
	DL_R [dB] Lab.	DL_{SI} [dB] In situ Elements	DL_{SI} [dB] In situ Post	DL_R [dB] Lab.	DL_{SI} [dB] In situ Elements	DL_{SI} [dB] In situ Post
Metallic cassettes with rock wool (2000)—Manufacturer A	24	31	32	28	35	35
Metallic cassettes with glass wool (2005)—Site A	25	31	28	30	37	33
Metallic cassettes with glass wool (2000)—Manufacturer B	26	32	33	32	39	38
Metallic cassettes with glass wool (2005)—Site B	26	32	32	32	39	37
Timber/Metal cassettes with glass wool (2005)	25	26	26	30	32	32
Concrete panels with a porous side	45	37	20	48	37	19
Framed acrylic sheets and concrete panels	33	34	31	33	36	32

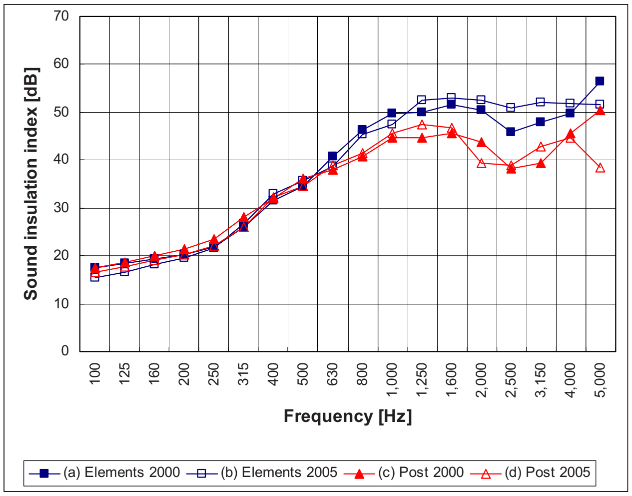

Fig. 15—Sound insulation index values measured on site B, where the metallic cassettes of a different manufacturer are installed, compared with the values obtained for the same products five years before.

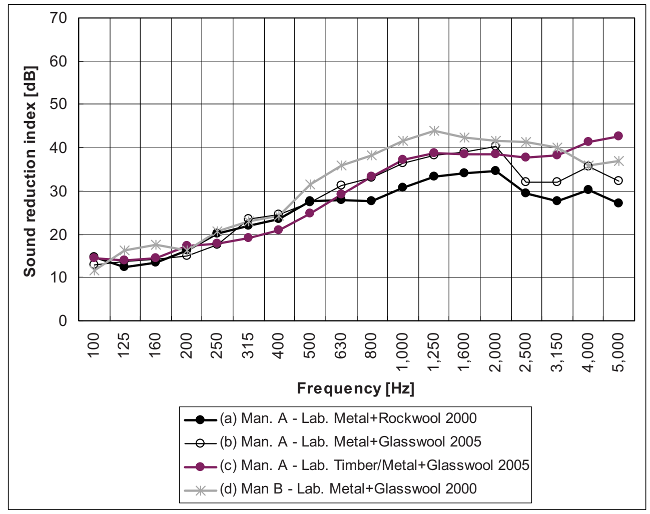

Fig. 16—Sound reduction index measured in the laboratory: (a) manufacturer A, full metal cassettes filled with rock wool; (b) manufacturer A, full metal cassettes filled with glass wool; (c) manufacturer A, timber/metal cassettes filled with glass wool; (d) manufacturer B, full metal cassettes filled with glass wool.

between the results obtained in the year 2000 and 2005 shows that the single number ratings have the same value for the measurements in front of the acoustic elements (32 dB road traffic spectrum, 39 dB high speed train spectrum) and differ for −1 dB only for the measurements in front of a post (33 dB vs. 32 dB road traffic spectrum, 38 dB vs. 37 dB high speed train spectrum). See Table 3. Now the maximum difference is −1 dB only, again for the measurements in front of a post.

Figure 16 shows the results obtained for the same products from manufacturer A and B in the laboratory in 2005.

In the laboratory the two products have a comparable performance; in situ, product B has a repeatable performance, within 1 dB, passing from year 2000 to year 2005. The drop of performance of product A in 2005 in front of a post cannot be attributed to the method or the measuring conditions alone, which are the same as for product B, and thus it should be due to a fault of construction or installation work. In other words, a non-visible sound leak has been detected. A possible explanation, typical for this kind of product, could be the non-optimal fitting of the cassettes into the post or the lack of sealing.

This suggests that CEN/TS 1793-5 method could be used as a mean to detect small sound leaks, not so easy to find by visual inspection, and to check the effectiveness of some design details.

5.2 Mixed Barriers in Timber and Metal

Figure 16 shows the airborne sound insulation curves measured in the laboratory for the same two samples of full metal and timber/metal cassettes, by manufacturer A: the two 2005 curves are reasonably similar until the 2 kHz 1/3 octave band and get the same single number rating (25 dB road traffic spectrum, 30 dB high speed train spectrum). The 2000 curve gets a single number rating of 24 dB using the road traffic spectrum and 28 dB using the high speed train spectrum (Table 3). Figure 13 shows the sound insulation index curve measured in situ in front of the timber/metal cassettes compared to the corresponding one for the full metal cassettes: the single number ratings are 5 dB less for the timber/metal cassettes than for the full metal cassettes. Figure 14 shows the sound insulation index curves measured in situ in 2005 in front of a junction between a post and the cassette. The single number rating shows a 2 dB difference using the road traffic spectrum (26 dB for the timber/metal cassettes and 28 dB for the full metal cassettes) and 1 dB difference using the high speed train spectrum (32 dB for the timber/metal cassettes and 33 dB for the full metal cassettes). As the differences are greater in front of the acoustic elements, it is suspected that they are due to the small leaks visible between the timber boards in the rear side of the timber/metal cassettes (Fig. 17). It should be noted that the comparison is based on data for the full metal barrier from site A where the panel/post junction is not the best (see discussion in Sec. 5.1), but the preceding conclusion is supported—as before—by the comparison with the

Fig. 17—The measurement junction between the timber boards on the rear side of timber/metal panels. The acoustic leak is indicated by the arrow (Picture taken during night time measurements).

laboratory data: Fig. 16 shows that in the laboratory the sound reduction index is almost the same for the timber/metal barrier and the full metal ones. The single number ratings are (see Table 3): 25 dB timber/metal 2005, 25 dB full metal 2005, 24 dB full metal 2000 (road traffic spectrum); 30 dB timber/metal 2005, 30 dB full metal 2005, 28 dB full metal 2000 (high speed train spectrum). If the sound insulation is almost the same in the laboratory, the 5 dB performance drop in situ in front of the acoustic elements suggests some faults in the timber/metal cassettes, and the visible leaks between the timber boards in the rear side are the most obvious candidates.

5.3 Concrete Barriers

The installed barriers are composed of massive concrete panels. The side facing the noise source is made of porous concrete, partly sound absorbing. These elements where tested in 2001 in the laboratory yielding a single number rating of 45 dB (road traffic spectrum)/48 dB (high speed train spectrum). When they are in place a reduced performance is expected, because of the lack of a groove-and-tongue junction between the elements and, even more important, of a proper fitting system between the panels and the metallic posts. Figure 18 shows the airborne sound insulation curves measured in the laboratory and in situ: as expected, the 45/48 dB rating obtained in the laboratory decrease down to 37 dB in situ in front of the concrete elements and to 20/19 dB in front of a post. Figure 19 clearly shows the primary reason for such a poor performance in situ: the conformation of the panels doesn't permit them to fit into the metallic posts, leaving a large gap. The lesson to be learned here is that it is useless to require massively insulating panels if

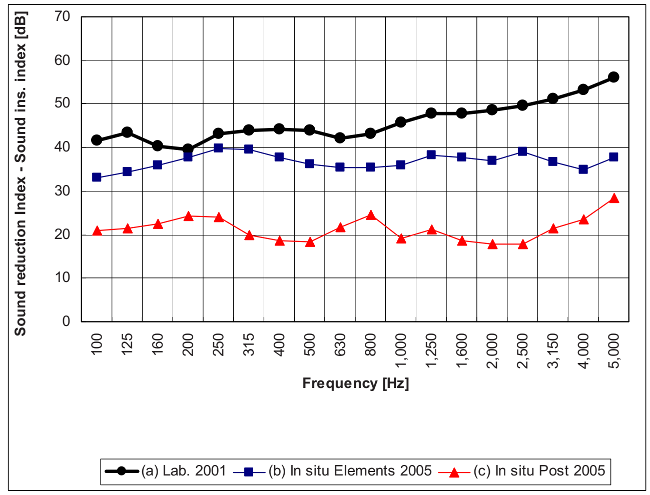

Fig. 18—Concrete barrier: (a) sound reduction index measured in the laboratory; (b) sound insulation index measured in situ in front of the concrete elements; (c) sound insulation index measured in situ in front of a post.

they are poorly fitted with each other and with the posts. A careful design of all components of the acoustic barrier and of their connections should never be forgotten. The in situ method clearly detected the fault, while the laboratory method, having been applied to a carefully sealed sample, didn't.

5.4 Acrylic and Concrete Barriers

The installed barriers are composed of acrylic sheets inserted into a metallic frame and supported by reflective concrete panels. Similar framed acrylic elements where tested in 1999 in the laboratory, without the concrete panels. Figure 20 shows the airborne sound insulation curves measured in the laboratory and in

Fig. 19—Top view of the measurement junction between a concrete element and a metallic post. The acoustic leak is clearly visible.

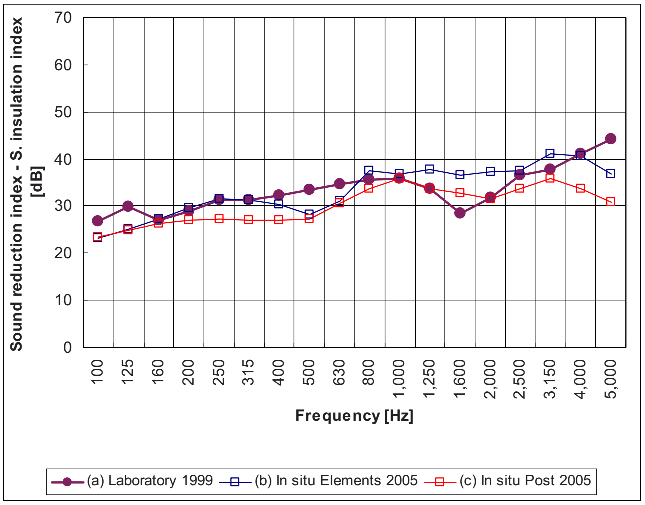

Fig. 20—Acrylic and concrete barrier: (a) sound reduction index measured in the laboratory; (b) sound insulation index measured in situ in front of the acrylic elements; (c) sound insulation index measured in situ in front a post.

situ. They confirm the general tendency for the laboratory results to be lower than the outdoors results for the same kind of barrier[6]. This is due to the different sound fields in front of the test specimen: diffuse field in laboratory and frontal free-field outdoors. In the laboratory, the oblique components of the diffuse field generate the coincidence effect, which of course is not possible outdoors. This means that when the framed acrylic elements are tested on site the coincidence dip is expected to disappear. Figure 20 shows the expected effect. On the other hand, sound leaks may be more pronounced on site, due to the difficulty of properly fitting the metallic frame to the concrete panels on a real construction site.

6 CONCLUSIONS

The in situ verification of the acoustic intrinsic characteristics of the noise barriers installed along the high speed railway line Torino-Novara gave the opportunity to check the CEN/TS 1793-5 procedure on a large construction site, where the operating conditions are very different from in the laboratory and when many measurements had to be conducted in a short time. The successful conclusion of the task is a strong argument in support to CEN/TS 1793-5 for on site testing.

The reliability of the measurements is supported by the comparison with the results of laboratory and in situ tests conducted four to six years before on similar noise barriers from the same manufacturers.

The CEN/TS 1793-5 procedure for sound reflection seems to give more realistic ratings, while the laboratory tests have the tendency to give the maximum allowed rating of sound absorption (20 dB) to all strongly absorptive products. Table 2 shows that metallic cassettes filled with rock wool, with glass wool or partly made with timber obtain the same single number rating of 20 dB irrespective of their differences. In situ values are more differentiated, even if small differences of 1 dB between the results for similar panels filled with rock wool or with glass wool may also be due to measurement uncertainty. In Sec. 4.4 an improvement for the next revision of CEN/TS 1793-5 has been suggested in order to avoid negative values of the single number rating DL_{RI}.

Airborne sound insulation measurements according to CEN/TS 1793-5 confirm the sensitivity of the method to detect faults of the product design or the workmanship which are not clearly visible at a first glance (see also Refs. 6 and 7). This is quite important because it has been shown that the single number rating for sound insulation close to the barrier can drop 4–5 dB in the case of metallic cassettes poorly fitted to their posts or timber/metal cassettes having leaks between the timber boards, and even more in case of concrete panels not shaped for the intended post. Apart from these faults, a distinction should be made between the differences in sound insulation found at different sites due to the typical variance of construction works and the uncertainty of the measurement method itself. While the latter still remains to be investigated, the presented results suggest a maximum difference between in situ measurements of sound insulation on similar samples—when properly installed—of 1–2 dB in the value of the single number rating, a performance comparable to that of the corresponding laboratory measurements (see Table 3).

The possibility to use the in situ method for fault detection paves the way to establish minimum construction and installation criteria, to be systematically verified on site after completion of the construction work.

Finally, the positive experience presented here suggests that the repeated application of the CEN/TS 1793-5 measurement method is feasible over long time intervals (5–6 years) in order to check the acoustic durability of traffic noise reducing devices, as recommended in EN 14389-1[12].

7 ACKNOWLEDGMENTS

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