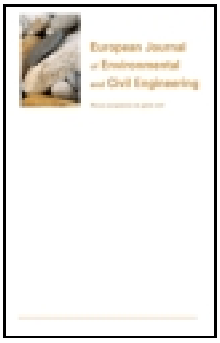


European Journal of Environmental and Civil Engineering
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tece20

Assessment of an industrial pavement via the impact acoustics method

Roberto Felicetti [a]
[a] DIS—Politecnico di Milano, piazza Leonardo da Vinci 32, 20133, Milano, Italy E-mail:

Available online: 05 Oct 2011

Assessment of an industrial pavement *via* the impact acoustics method

Roberto Felicetti

DIS - Politecnico di Milano
piazza Leonardo da Vinci 32
20133 Milano - Italy

roberto.felicetti@polimi.it

ABSTRACT. *Industrial pavements often represent a critical issue in Civil Engineering. Shrinkage strain, excessive deflection, fatigue loading, incompatibility among different concrete layers are some common problems which may lead to an extensive damage in this type of structure. Such inconveniences usually involve quite large areas, calling for efficient Non-Destructive techniques in order to perform a thorough inspection of the pavement conditions. In this paper the impact-acoustic technique has been regarded as a method for detecting the delamination occurring under the abrasion-resistant top coating of concrete ground-slabs. The implementation via affordable tools for digital audio recording, the proper processing of the audio files and the procedure for drafting the damage maps are discussed in the paper with reference to the case study of a warehouse building.*

RÉSUMÉ. *Dans cet article, la technique d'impact acoustique a été considérée comme une méthode pour la détection du décollement prenant place sous la couche d'enduit abrasorésistante supérieure de la couche de béton. L'implémentation à partir d'outils d'enregistrement audionumérique à coût raisonnable, ainsi que le traitement de ces fichiers audio et l'ébauche d'une procédure de cartographie de l'endommagement sont discutés dans cet article avec référence au cas d'étude d'un entrepôt.*

KEYWORDS: *delamination, impact acoustics, hammer tapping, pavements.*

MOTS-CLÈS : *délaminage, acoustique d'impact, martelage, revêtement.*

DOI:10.3166/EJECE.14.427-439

1. Introduction

One of the most common problems in the assessment of civil structures is the detection of superficial defects and delamination cracks over large areas. Abrasion-resistant coatings in industrial pavements, topping concrete in precast decks, tiles and plaster in building facades are just some examples of surface covering layers whose bond to the substratum may fail as a consequence of execution errors, repeated loading or durability problems.

Several advanced ND techniques are available for the assessment of this kind of defects. The discussion of their potentials and limitations with reference to the problem in question is one leading task of the RILEM Technical Committee 207-INR (Interpretation of NDT results and assessment of RC structures).

An example are the impact-and pulse-echo techniques (Krause *et al.*, 1997), based on the propagation of short pulses which are partly reflected by the interfaces in the material (see Figure 1a). These methods are widely used for revealing the thickness of concrete members or the presence of voids and sizeable discontinuities The duration of the pulse (generally not less than 20 μs) determines the minimum time-of-flight of a returning stress-wave which can be recognized after exciting the structure, and then the minimum depth of a defect that can be detected *via* this method (in the order of 40 mm). This is a significant limitation in many applications.

Another effective method is the infrared thermography, which relies on the easy measurement *via* a special camera of the thermal radiation ensuing from the surface of a member, as a function of its temperature and emissivity. The presence of hidden cracks and interfaces is revealed by their effect on the transmission of natural (day-night cycle) or actively imposed thermal transients through the investigated member. Due to the low thermal diffusivity of concrete, quite a long time is needed for a thermal pulse to penetrate a structure. Then the implementation of this method turns out to be remarkably slow for indoor applications, where a preliminary heating of the structural members is generally required (Weritz *et al.*, 2003).

Other promising techniques may be cited, like the analysis of surface waves, the ground penetrating radar and the electrical resistivity measurement. Nonetheless, their implementation generally requires sophisticated instruments and experienced personnel, they are not always viable over large areas and their application is usually limited to well defined ranges of depth, size and intensity of the defects.

Despite this wide assortment of advanced investigation techniques, it is not rare, during the first inspection of a damaged structure, to locate the defective parts at issue by repeatedly tapping the members with a common hammer. Compared to impact-echo, this approach takes roots in the low frequency flexural vibrations governing the impact response of the concrete layer above a near-surface delamination crack (depth $\leq 0.5\cdot$diameter - Figure 1a).

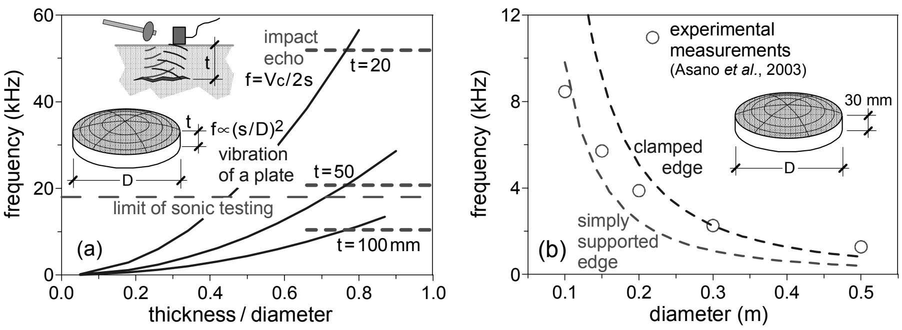


Figure 1. *a) mechanisms governing the acoustic response of a delaminated layer and b) comparison between the experimental results (Asano* et al.*, 2003) and the natural vibration frequency of circular plates*

In fact, the method can be made more objective and rigorous by recording and properly processing the sound of the hit surface, leading to the impact acoustics technique. The use of microphones in the response analysis has been already reported in the literature (Zhu *et al.*, 2006; Haya *et al.*, 2003) and the good agreement with the traditional contact measurement has been proved in a frequency range up to 10 kHz (Asano *et al.*, 2003).

In most studies the attention is focused on the dominant peak of the frequency spectrum, which is closely connected to the size and depth of the delamination crack (Figure 1). As an alternative, the acoustic signal at each frequency can be divided by the corresponding intensity of the excitation pulse, in case an instrumented hammer is adopted. This lead to the so called mobility plots (Davis *et al.*, 2005), whose shape is related to the stiffness of inspected member and to the possible local defects (honeycombs and debonding of layers). However, it has to be remarked that the delamination of flooring coatings often goes with a diffuse cracking of the detached plates, whose response can be hardly interpreted with rigorous mechanical models.

In this paper the implementation of the impact acoustics technique by means of easily available low-cost devices is discussed, in the perspective of a systematic application to large industrial pavements. The problem of repeatedly hitting the concrete floor has been solved by means of a specially designed trolley, whose front wheels activate a small hammer fitted with a plastic head. The apparatus is completed by a condenser microphone and a digital audio card connected to a laptop computer. The recording of each blow is then processed in order to work out a scalar indicator of the local conditions of the surface layer.

This setup has been developed and used for the assessment of a large pavement in a logistic centre. The particular aspects and the operative restrictions which have been faced in this onsite application will be discussed first, in order to emphasize the practical intention implied by this approach.

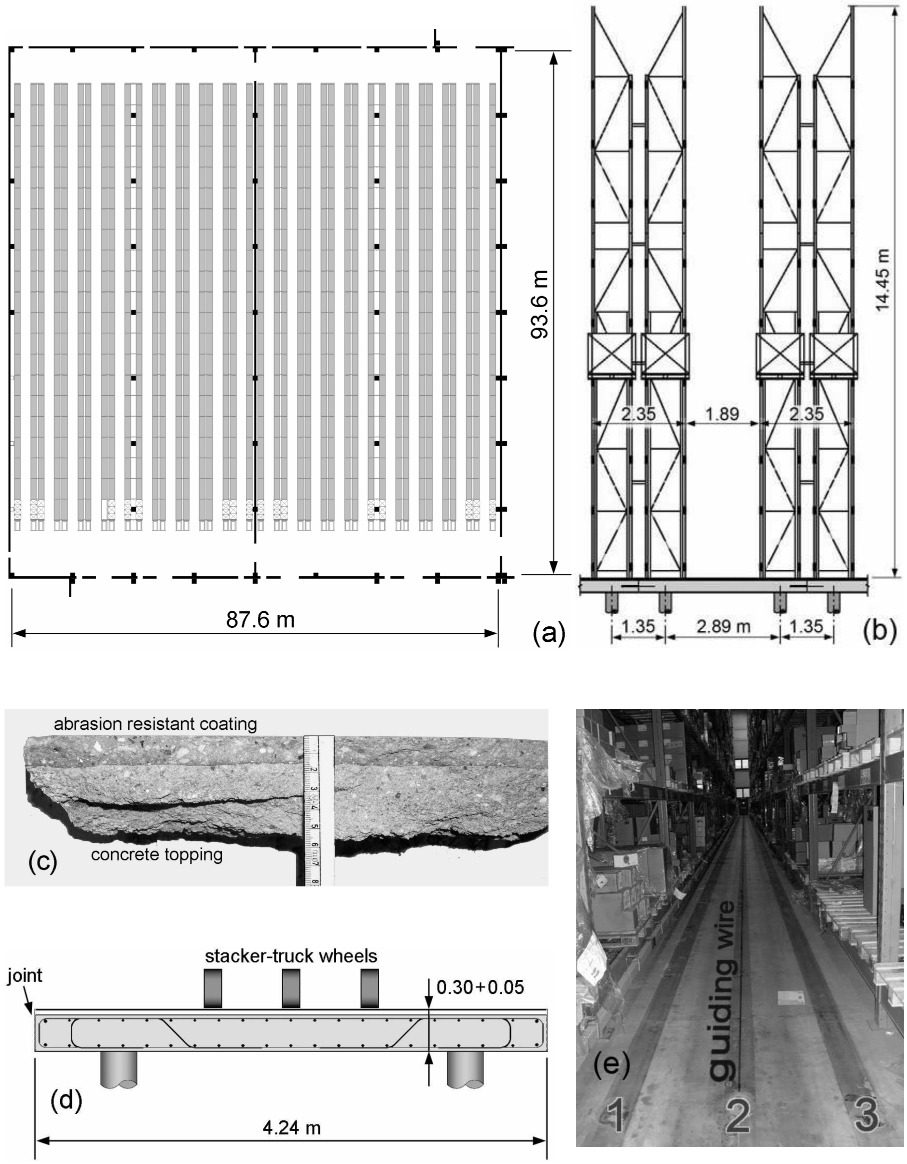


Figure 2. *a) plan of the investigated warehouse facility; b) cross section of an aisle between the racks;(c) concrete layers forming the 50 mm thick pavement; d) ground-slab strip supported by piles and e) view of an aisle and its flooring*

2. Case study and its practical implications

The warehouse building at issue covers an area of about 8 200 m^2 and it is organized in 40 pallet racks served by 20 access aisles (W x L = 1.9 x 80 m – Figure 2a). The racks are 14.5 m high (Figure 2b) and can be reached by means of electric stacker-trucks precisely guided along the axis of each passageway by an automatic steering system. As a consequence, the three wheels of the trucks repeatedly tread on exactly the same lines, which are materialized by as many visible tracks on the flooring (see Figure 2e).

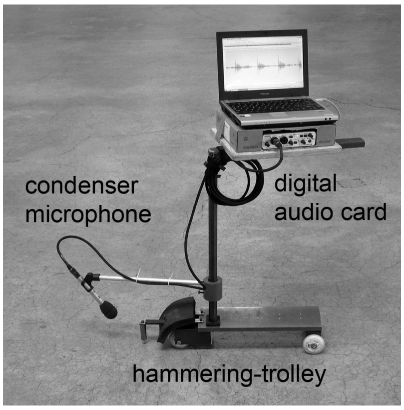
The pavement is based on a 0.30 m thick R/C ground-slab resting on foundation piles, and it is made of a 35-40 mm topping layer finished with a 15 mm abrasion-resistant quartz-concrete coating (Figures 2c, 2d). Detachments of this latter coating have been observed in a number of points along the wheel tracks, as a consequence of the repeated loading-unloading process due to the transit of the stacker-trucks. The reason for this kind of damage may be ascribed to both the not uniform quality of the topping concrete and the bending deformability of the ground-slab, made apparent by a diffuse pattern of transverse cracks on the pavement.

It is clear that the detachment of even a small portion of the floor represents a severe danger for the operations of the stacker-trucks, given their considerable elevation and the relatively tight interval between the racks. For this reason, the building owners decided to undertake the required repair works, under the condition of minimizing the impact on the continuous activity of this facility, which is paused just for one day and half in the weekends.

The first step was to produce a map of the potentially dangerous stretches of the aisles, including some indication on the level of severity of the local condition of the pavement. During the first inspection of the structure it was evident that the critical spots were quite easy to recognize, thanks to the hollow sound ensuing when tapping the surface with a common hammer or a broomstick. The open issue was to categorize the different conditions in a more objective way and to be able to scan the whole pavement within one weekend-pause in the logistic centre activity. Due to the localization of the critical spots on the three well visible wheel tracks, it was decided to scan each passageway along four lines, being the central strip divided by the guiding wire of the automatic steering system. This arrangement implies the inspection of a total path of about 6.4 km in the aisles and 0.6 km in their common access area.

3. Investigation technique

The problem of tapping the concrete floor at regular intervals along prescribed lines has been solved by means of a specially designed hand-driven trolley (Figure 3). The device consists of a rather heavy steel plate fitted with four soft rubber wheels mounted on ball bearings. This assembly allows a silent motion with no skid of the wheels, whose rotation is then strictly connected to the current position of the trolley. On the front side the rotation activates a cam mechanism, which gradually raises and suddenly drops a 0.2 kg hammer fitted with a hard plastic head. The interval between two consecutive taps is 75 mm and the optimum operating pace is in the range between 1 and 6 taps per second. Hence, this device allows to perform one scan along a 80 m aisle in about 5 minutes (1 066 taps).



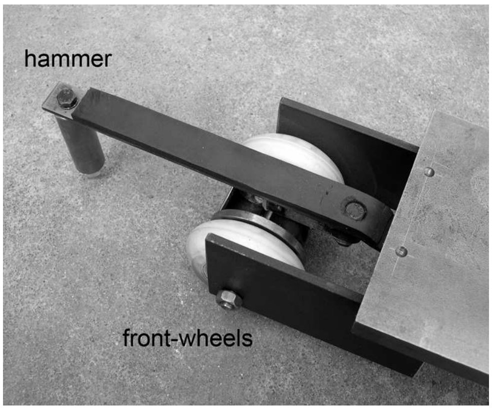


Figure 3. *The hammering-trolley fitted with the audio acquisition system and details of the hammering mechanism driven by the front wheels*

The pavement response was captured, while dragging the trolley, via a condenser microphone (AKG 451B, ± 4 dB@30 Hz ÷ 20 kHz) and a USB digital audio card (Edirol UA-25) connected to a laptop computer. Compared to the built in audio system of the computer, the adopted card includes a better quality amplifier and provides the phantom voltage required by this type of microphone to operate. As an alternative, pre-amplified battery powered microphones are available on the market, which can be directly connected to the analog audio input of an ordinary laptop (Haya *et al.*, 2003). Some microphone-to-USB digital adaptors (CEntrance MicPort Pro, Shure X2u, etc.) are another interesting option to fit any computer with a measurement microphone. In an updated version of this system, a dynamic load cell has been mounted between the hammer mass and the plastic tip, taking advantage of the second channel of the stereophonic audio card herein adopted.

The digitalized signal (44.1 kHz – 16 bit) was stored in the computer memory in the form of uncompressed audio files, to be subsequently processed in order to work out a scalar indicator of the local flooring condition. Parallel to the audio recording, a simple software was run, whose purpose was simply to annotate the coordinated typing of prearranged hotkeys, which were associated to particular faults observed on the pavement (transversal cracks or patches covering former delaminations). This allowed to draft also a map of the visually surveyed defects in the flooring.

4. Data processing

The remarkable amount of data collected while tapping the 20 aisles of the logistic building (about 2 GBytes of digital audio files) has been processed through series of steps in order to condense the relevant information into a map of the damage severity.

In general, the signal recorded after a single hammer blow exhibits two well distinct components: an initial wave of relatively high frequency (in the order of 1 kHz), which tends to fade away within about 30 ms, and a more stable wave of well defined frequency (180 Hz), starting 5-10 ms after the hammer blow (Figures 4a, 4b). These two parts can be easily recognized on the frequency distribution diagrams (magnitude of the Fast Fourier Transform - Figure 4c). The first component is associated to the pavement response and it is strongly related to its local condition, to the point that it nearly disappears in the case of a sound flooring. The lower frequency part is to be ascribed to the mechanical vibration of the arm activating the hammer and it is a function of the tap intensity, which may be slightly affected by the variations in the hammer rebound and in the trolley speed (coefficient of variation ≅ 8%).

As already discussed, several studies in the literature focus the attention on the dominant frequency of the recorded sound, due to its possible theoretical connection with the depth and diameter of a delaminated area (Asano *et al.*, 2003). Unfortunately, the detachment of flooring coatings often goes with a diffuse cracking of the detached plates, which exhibit a reduced vibration frequency due to the lower bending stiffness. On the other hand, it has been observed that the sound intensity is a sensitive and robust parameter, that is in good correlation with the severity of the local damage, though no clear relationship has been worked out with the geometrical features of the defect.

Based on this line of reasoning, a procedure for data processing has been implemented, that can be summarized in the following steps.

A) Detection of the hammer blows (denoted by a steep variation of the recorded signal). Counting the equally spaced blows allows also to determine the current position of the trolley along the scanned line and then to assign the results to well defined points.

B) Computation of the frequency spectrum. This has been performed by extracting a set of 2048 samples (corresponding to a 46 ms signal) to be processed via the Fast Fourier Transform. The main features of the frequency distribution diagrams have been already discussed (see Figure 4c). Only the relevant range up to 4 kHz has been considered in the following steps.

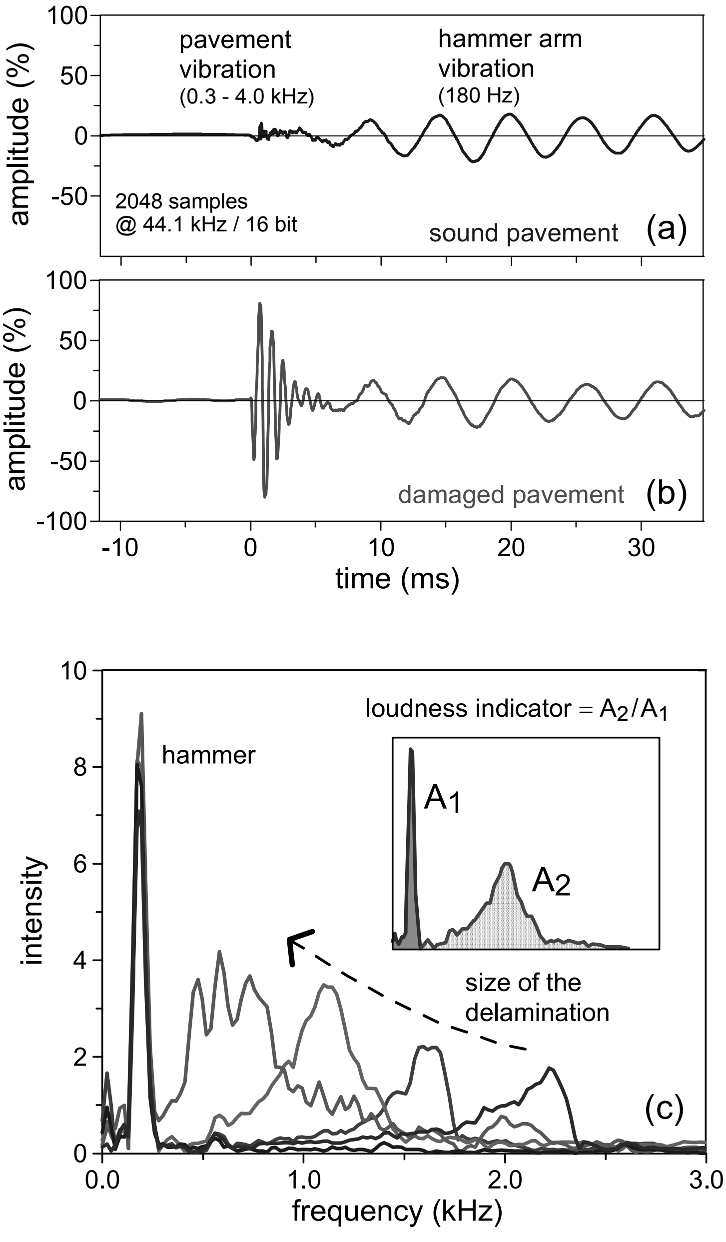


Figure 4. *Typical recorded signals following a hammer tap on either: a) a sound or b) a damaged pavement; c) frequency spectra at increasing size of the delamination crack and definition of the loudness indicator*

C) Calculation of a dimensionless loudness indicator for each hammer blow. In order to separate the flooring response from the vibration of the hammering mechanism, the average intensity of the sound ensuing from the pavement has been defined as the area A2 below the magnitude spectrum in the frequency range 0.26-4.0 kHz (Figure 4c). This value has been divided by the spectrum area A1 in the frequency range 0.13-0.26 kHz, which allows for the intensity of the hammer blow. The dimensionless ratio A2/A1 is usually not greater than 5 for sound concrete, but it can exceed a value of 50 for severely delaminated areas (Figure 5a).

D) Application of a threshold and normalization into a damage index. Each 80 m long scan involves a series of 1 066 measurements of the loudness indicator. In order to clearly distinguish any damaged area of the pavement an adaptive threshold has been defined based on the average value and dispersion of the signal emanating from sound concrete (Figure 5a). All the values exceeding this local limit have been normalized on the average loudness of the remaining points and a damage index has been finally worked out.

E) Classification of the damage levels and plotting of the damage map. In the 20 access aisles a total of about 2 400 measurements out of 85.000 led to a louder response than the local threshold, indicating a possible incipient detachment of the pavement coating. The incidence of these damage values is shown in Figure 5b, together with the colour scale adopted to summarize the results into damage plots.

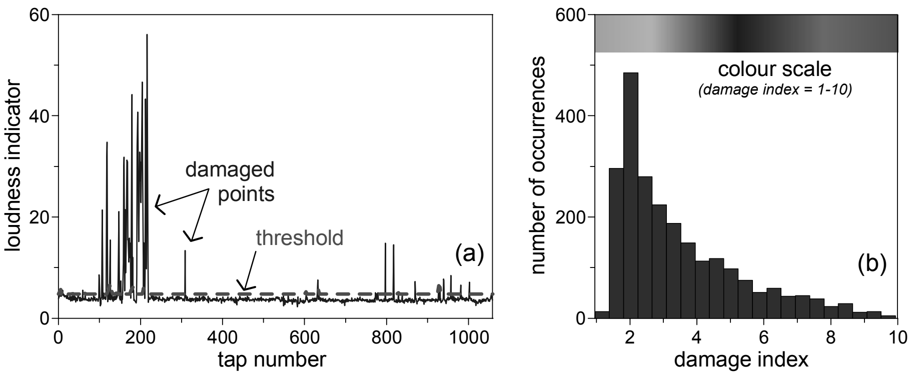


Figure 5. *a) Loudness indicator along one 80 m line (1 066 taps) compared to the adaptive threshold for distinguishing the damaged points and b) number of occurrences of the different damage levels and associated colour scale for drawing up the damage map*

The whole procedure above discussed has been implemented in a dedicated software whose final output is a schematic map of the warehouse facility (Figure 6). In the map the aisles are symbolized by the numbered light-grey strips where the damaged points of the four scanned lines are indicated by coloured pixels. The longitudinal reference is provided by the lettered black points on white background, indicating the upright supports of the racks arranged at 3.7 m intervals (see Figure 2a).

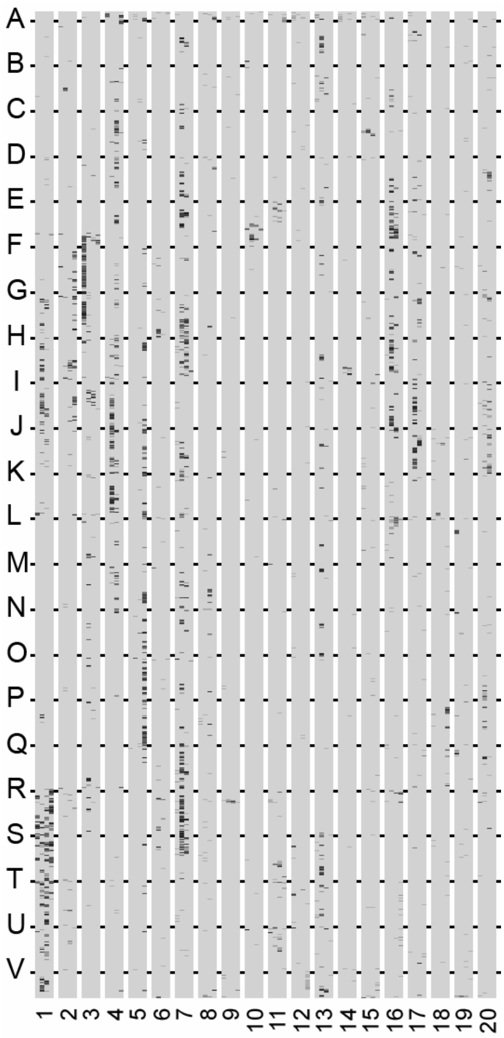


Figure 6. *Map of the pavement damage in the inspected logistic facility*

aisle #1 – position G	*truck passages not frequent* *high pavement damage – edge of the slab*	3.29 2.68 1.89 1.62 **2.37 N/mm^2**
aisle #2 – position H	*frequent truck passages* *limited pavement damage*	1.47 1.25 1.32 **1.35 N/mm^2**
aisle #4 – position H	*truck passages not frequent* *high pavement damage*	1.28 0.95 0.24 0.44 **0.73 N/mm^2**
aisle #19 – position J	*frequent truck passages* *limited pavement damage*	3.63 1.77 1.13 **2.18 N/mm^2**
aisle #20 – positions K	*frequent truck passages* *high pavement damage*	1.28 1.96 1.43 0.99 **1.42 N/mm^2**

Table 1. *Results of the pull-out tests*

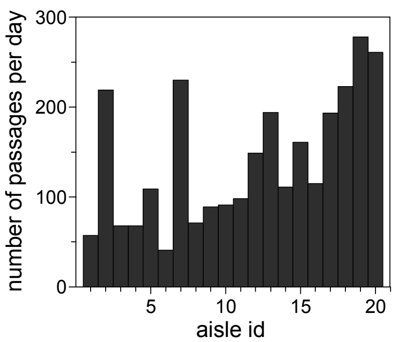


Figure 7. *Frequency of the stacker-trucks passages in the access aisles*

5. Test results

After having examined the damage map of Figure 6, the critical parts of the inspected area are quite evident, in the form of coloured stretches extending for 2-4 rack modules along the aisles. The different hues express the whole damage range from incipient (cyan) to completely developed (blue to red) delamination of the pavement coating. It transpires that there are several portions of the pavement which are likely to experience the detachment of the abrasion-resistant concrete coating, especially in the first seven aisles and in aisles 16 and 17.

Other significant data were provided by a series of pull-out tests performed on the pristine flooring below the storage racks, in order to the give an account on the inherent quality of the topping concrete layer and on its bond to the underlying substructure (Table 1). These tests consist in the preliminary cut of a 50 mm diameter core until concrete ground-slab is reached and in its subsequent pulling via a glued steel plate. The results exhibit a considerable scattering, even between adjacent test areas. This evidence gives reasons for the chaotic distribution of the damaged stretches of the flooring. On the contrary, the density of the transversal cracks due to bending of the foundation slab is almost uniform. Beyond confirming the general deformability of the pavement, no apparent connections can be recognized between the crack pattern and the damage map.

Finally, the histogram of the relative frequency of the stacker-trucks passages in each aisle is presented in Figure 7, according to the data provided by the building management. It transpires that this parameter doesn't play a key role in determining the damage pattern.

6. Inspection of the repaired pavement

Following the assessment of the pavement conditions, an appropriate repair technique has been designed, in order to fulfil a series of practical requirements: short interruption of the operations in limited parts of the facility, most favourable balance between materials and labour costs, substantial improvement of the pavement durability regardless of the local conditions of the supporting ground-slab. The technique is based on the replacement of the pavement layers only along three 0.3 m strips, slightly exceeding the trails of the truck wheels (Figures 8a). The adopted material is a high-performance epoxy-based grout, whose long-term connection to the substratum is guaranteed by a series of 8 mm stirrups arranged at 0.20 m intervals and glued into drilled holes.

Despite the excellent quality of the grout (compressive strength = 110 N/mm^2, splitting strength = 11.4 N/mm^2), some pull-out tests on a trial repair patch highlighted the unsatisfactory bond to the concrete substratum (~1 N/mm^2). For this reason, one month after opening to service the first repaired aisle, a new check has been performed via the described impact acoustics technique. The outcome is that in no point the response to the hammer taps could be ascribed to a faulty zone. The check was extended also to the remaining intermediate strips of the old flooring, obtaining somewhat worse results (maximum damage index slightly higher than 1). Though less influenced by the moving loads, these latter parts were in fact just marginally stabilized by the side repair patches.

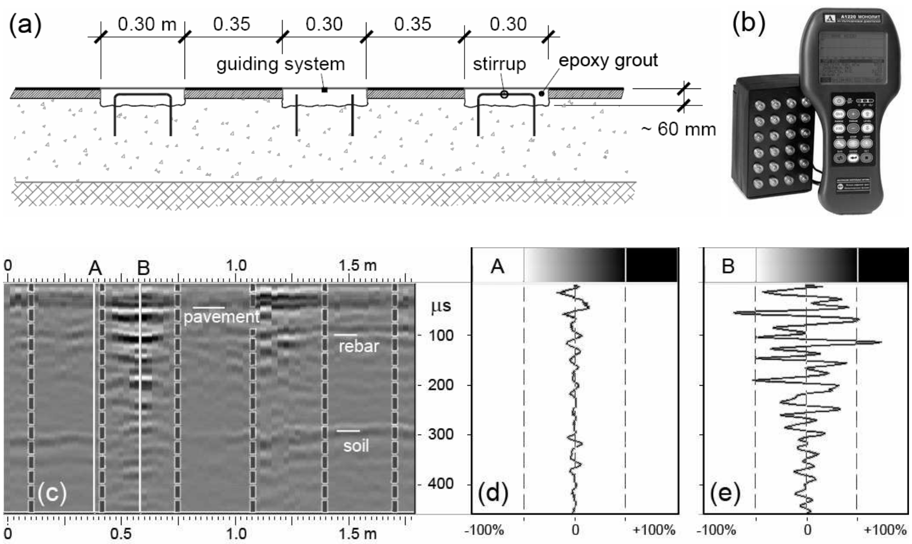


Figure 8. *a) cross-section of the repaired pavement; b) ultrasonic device for the implementation of the shear pulse-echo technique; c) B-scan across a repaired cross-section and d)-e) A-scans pertaining to a repaired point and to a remaining piece of the old pavement*

In order to deepen this aspect, the shear waves pulse-echo technique has been implemented along a transversal cross section of the aisle. A dedicated instrument has been used (Acoustic Control Systems A1220 - Figure 8b), in which the transmitting and receiving sensors are integrated in a single array of 12 + 12 dry-contact point transducers. The results, either in the form of time-amplitude plots (A-scans, Figures 8d, 8e) or time-position-intensity cross-sections (B-scan, Figures 8c), confirm the definitely good response of the repaired parts of the pavement, with just very low reflections corresponding to the depth of the steel reinforcement and of the soil interface (after 100 and 300 µs - Figures 8c, 8d). Across the old lining the far stronger signal supports the indications of the hammer-tapping technique (Figures 8c, 8e). In actual fact this response can be hardly ascribed to the multiple reflections of the ultrasonic pulse, being the delamination too shallow compared to the recognized limit of applicability of this device. On the contrary, the period of the received wave (~ 35 µs) can be ascribed to the second mode of vibration of the delaminated plate, which is excited by the shear pulse applied on the surface. This interpretation is corroborated by the comparison with the dominant frequency detected via the impact acoustics technique, which is consistent with the expected ratio between the first two natural vibration frequencies of the circular slabs.

7. Conclusions

In this paper a practical implementation of the impact acoustics technique has been discussed, aimed at the assessment of the diffuse delamination of the abrasion-resistant coating in large industrial pavements. The specially designed setup, based on low-cost and easily available devices, allowed to survey the 8 200 m^2 flooring of a logistic area in about 8 hours. An automated data processing procedure allowed to condense in a damage map both the location and the severity of the identified faults. A direct comparison with the shear waves pulse-echo technique confirmed the consistency of the two techniques, though this latter proved to be more sensitive at the cost of much slower operations.

As is common in NDT assessment of real structures, the most promising approach should be based on merging efficient but generally sketchy methods with more accurate local measurements performed by means of the advanced and more demanding techniques.

8. References

Asano M., Kamada T., Kunieda M., Rokugo K., "Impact acoustics methods for defect evaluation in concrete", *Proceedings International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE)*, Berlin, 2003.

Davis A.G., Lima M.K., Germann Petersen C, "Rapid and economical evaluation of concrete tunnel linings with impulse response and impulse radar non-destructive methods", *NDT&E International*, vol. 38, n° 3, 2005, p. 181-186.

Haya H., Luo X., Uomoto T., "Study on impact acoustic method and system development based on wavelet", *Proceedings International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE)*, Berlin, 2003.

Krause M., Bärmann M., Frielinghaus R., Kretzschmar F., Kroggel O., Langenberg K.J., Maierhofer C., Müller W., Neisecke J., Schickert M., Schmitz V., Wiggenhauser H., Wollbold F., "Comparison of pulse-echo methods for testing concrete", *NDT&E International*, vol. 30, n° 4, 1997, p. 195-204.

Weritz F., Wedler G., Brink A., Röllig M., Maierhofer C., Wiggenhauser H., "Investigation of concrete structures with Pulse Phase Thermography", *Proceedings International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE)*, Berlin, 2003.

Zhu J., Popovics, J.S., "Air-coupled impact-echo imaging of concrete structures", *Proceedings of NDE Conference on Civil Engineering*, St. Louis, 2006, p. 423-428.