Construction and Building Materials 48 (2013) 1302–1308

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Inspection, evaluation and repair monitoring of cracked concrete floor using NDT methods

Nikolaos Zoidis [a], Efthymios Tatsis [b], Christos Vlachopoulos [a], Anastasios Gotzamanis [c], Jesper Stærke Clausen [d], Dimitrios G. Aggelis [e], Theodore E. Matikas [b,*]

[a] Geotest SA, Ioannina, Greece
[b] Materials Science & Engineering Dept., University of Ioannina, Greece
[c] Earthquake Engineering, Ioannina, Greece
[d] Ramboll Denmark A/S, Copenhagen, Denmark
[e] Dept. of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Belgium

HIGHLIGHTS

- Investigation of causes that have led to extensive cracking on concrete floor surface.
- Cracks recording and crack depth estimation by ultrasound pulse velocity measurements.
- Investigation for voids under concrete floor slab using the Impulse-Response method.
- Concrete floor width estimation using the Impact-Echo method.
- Grout injections monitoring using the Impulse-Response method.

ARTICLE INFO

Article history:
Available online 26 July 2013

Keywords:
NDT
Impact-Echo
Impulse-Response
Ultrasound pulse velocity measurements
Crack depth estimation
Repair

ABSTRACT

The objective of the present study is the evaluation of the condition of the concrete floor that suffers from extensive cracking on its surface, through systematic tests using NDT methods. The study contained a thorough visual inspection and recording of cracks, estimation of the crack depth using ultrasonic pulse velocity measurements, investigation for voids between the concrete floor and the underlying aggregate layer using the Impulse-Response method, concrete floor thickness estimation using the Impact-Echo method and concrete quality estimation using cores cutting. The purpose of the study was to investigate the causes that led to extensive cracking on the floor surface in order to plan the repair strategy. The repair method that was chosen was based on grout injections in order to fill the voids located between the concrete and the underlying aggregate layer. The injections were executed in a triangular grid and were monitored using the Impulse-Response method. The area, where the injections took place, was inspected using the method before and after the injections and a secondary grid was designed taken into account the results. After injecting in the secondary grid, the area was inspected again using the Impulse-Response method in order to confirm the successful filling of the voids.

1. Introduction

The object of this paper is the assessment of the present condition of an extensively cracked concrete floor that is based on ground using non-destructive testing methods, as well as the testing of the underlying aggregate layers of the sub-base.

The purpose of this research was the investigation of the causes that have led to the extensive cracking on the surface of the floor. This was necessary in order to plan the optimal repair strategy considering the causes, as well as finding positions and problems that need special attention during the repair.

The tests were conducted at a warehouse for comestibles and drinks, with loading and unloading docks as well as areas of cooling and freezing. The appearing cracks degrade the ride quality and significantly hinder the movement of lift tracks and pallet trucks, vehicles used for transporting, sorting and loading of products.

According to construction plans the concrete floor is 180 mm thick and is constructed by concrete of C25/30 class, reinforced with steel fibers with hooked ends, in a content of 35–40 kg/m^3

* Corresponding author. Tel.: +30 26510 07216.
E-mail addresses: geotest@geotest.gr (N. Zoidis), etatsis@gmail.com (E. Tatsis), cvlacho@gmail.com (C. Vlachopoulos), acg@teemail.gr (A. Gotzamanis), JTC@ramboll.dk (J.S. Clausen), daggelis@vub.ac.be (D.G. Aggelis), matikas@otenet.gr, matikas@cc.uoi.gr (T.E. Matikas).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.06.082

by weight. The sub-base of the floor consists of two layers of crushed gravel aggregate, 250 mm thick. The floor has metal joints that divide the surface into independent sections of approximately 1200 m^2.

The survey included non-destructive tests to determine the depth of the cracks using ultrasonic pulse velocity measurements. Though it was not feasible to measure all cracks given the restrictions of time and logistics, several large cracks were measured as a representative measure. The depth of the cracks was measured in order to check if they had penetrated through the whole thickness of the slab. This gives the crucial information about if the floor exhibits serious discontinuities in its structures and is something necessary for the repair assessment. Another aim was to investigate the existence of voids between the floor and the substrate using the Impulse-Response method (ASTM C1740-10) and to determine the thickness of the concrete floor using the Impact-Echo Method (ASTM C1383). The survey also included a visual inspection (recording of all the appearing the cracks by position, width and length) and cores cutting for concrete class determination. The concrete cores that were cut off were also used to calibrate the results of the non-destructive testing methods that were used. Finally, elevation control of the floor, as well as compaction and quality testing of the sub-base material were carried out [6].

The paper also includes details about the repair with grout injections and the repair monitoring using extensive use of the Impulse-Response method in a part of the warehouse.

2. Testing methodology

2.1. Determination of crack depth using ultrasonic pulse velocity measurements

The determination of the depth of the cracks appearing on the floor was done using ultrasonic pulse velocity measurements and complementary, to calibrate measurements cores were cut off to test and calibrate the deviation of measurements.

The estimation of the crack depth with ultrasonic pulse velocity measurements relies on the fact that the existence of cracks or internal discontinuities in concrete cause diffraction to the propagation of ultrasonic pulse. This increases the propagation time and the velocity appears to be reduced [4].

The process of calculating the depth of an ultrasonic surface crack perpendicular to the surface is as follows [1].

- Measuring of the transit time between the pulser and the receiver (t_c) at a healthy part of the concrete
- Measuring of the transit time while placing the pulser and the receiver on both sides of the crack (t_p)
- Calculation of the crack depth by the following equation.

$$d = \frac{L}{2}\sqrt{\left(\frac{t_c}{t_p}\right)^2 - 1} \quad (1)$$

where d = crack depth, L = distance between transmitter and receiverFor the measurements, the PUNDIT ultrasonic equipment from PROSEQ company and portable Surfer's from ACS company were used. (Fig. 1).The measurements were calibrated by concrete cores cutting.

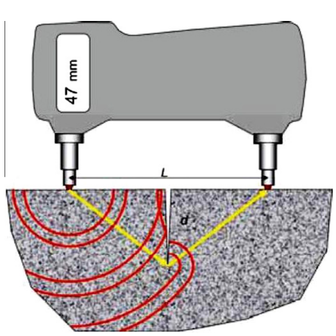

Fig. 1. Crack depth measurement using ultrasonic pulse velocity measurements (www.germann.org).

2.2. Investigation of voids existence between floor and substrate

To investigate the existence of voids between floor–substrate and suspected areas with problem was carried out using the Impulse-Response method (ASTM C1740-10).

The operating principle is based on a low strain impact produced by a hammer with a rubber tip. The impact causes vibrations in the element and stimulates primarily flexural form. A velocity receiver set adjacent to the point of impact, records the response. The load cell and the velocity receiver are connected to a laptop computer and by using appropriate software the results are analyzed. When the material below the impulse is stiff and homogeneous, the excitation by impulse cannot excite large scale vibrations due to the small amount of energy offered externally. On the other hand if there is delamination or voids beneath the surface this energy is sufficient to trigger larger amplitude vibrations and this is measured by the average mobility. Specifically, the function of the force in time, produced by the hammer and the measured velocity response is transformed in the frequency domain using the Fast Fourier Transformation (FFT). The range of velocity response divided by the range of force is called "mobility" and is a function of frequency. The mobility is given in units of speed per power (m/s)/N [2].

The parameters of the mobility diagram (Fig. 2a) used for assessing integrity are:

- The dynamic stiffness, the inverse of the initial slope of the mobility spectrum from 0 to 40 Hz, expressed in units of N/m.
- The average mobility (lined bar).
- The mobility slope between 100 and 800 Hz.
- The voids index (the ratio between the width of the initial maximum mobility to the value of the average mobility).

The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). High values of average mobility are directly related to the density and the thickness of a plate element. A reduction in plate thickness corresponds to an increase in average mobility [1].

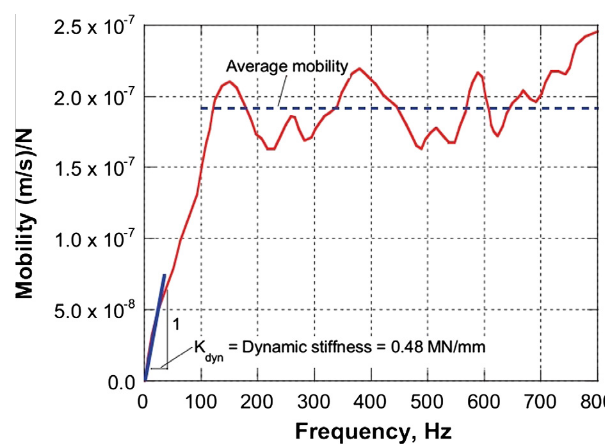

Fig. 2a. Mobility diagram and the used parameters.

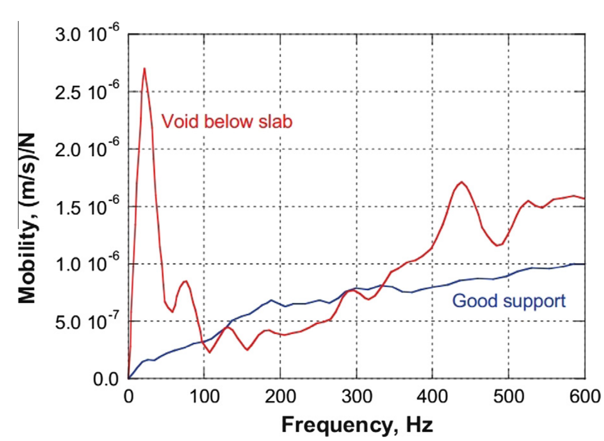

Fig. 2b. Mobility diagram for ground floor with and without void.

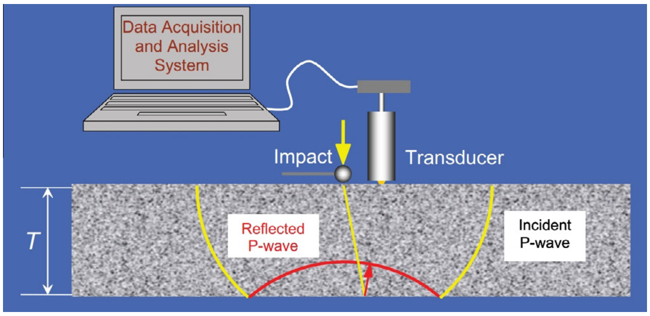

Fig. 3. Operating principle of the Impact-Echo method.

An example is shown in Fig. 2b which compares the mobility of a ground floor with the existence of a void underneath and the mobility of a solid ground floor [5].

The s'Mash system, of GERMANN INSTRUMENTS company was used for the testing (www.germann.org).

2.3. Determination of concrete thickness

The determination of the concrete thickness was made with the Impact-Echo method (ASTM C1383). Under this method, a short duration pulse produced after impact is propagated within the element. From the point of impact three types of elastic waves are produced. A surface wave (Rayleigh) travels along the surface and the P (longitudinal) and S (shear) waves are propagate within the element. The Impact-Echo method utilizes P waves.

When the P waves reach the opposite surface of the test element, they are reflected and propagate towards the surface where the impact was excited. A sensitive receiver positioned adjacent to the point of impact record the movements produced by the waves on the surface of the element. The P waves reflected further on the impact surface and the cycle starts again. The P waves are repeatedly reflected between the two opposite surfaces. The received waveform of surface movement exhibits a periodicity related to the thickness of the element and the wave velocity [3].

The waveform is transformed from time domain to frequency domain (Fourier transform) and the frequency of P waves is calculated. The thickness of the element (T) is related to the frequency (f) and waves speed (Cp) on the following equation [2]:

$$T = C_p/2f \tag{2}$$

The measurements were calibrated by concrete cores that were cut off, as will be discussed.

The DOCter system from GERMANN INSTRUMENTS company and the layout shown in Fig. 3 was used for the measurements.

3. Results presentation and evaluation

3.1. Crack depth measurements using ultrasonic pulse velocity measurements

After the recording of the appearing cracks (as shown in Fig. 4), crack depth measurements were carried out using ultrasonic pulse velocity measurements for cracks of various surface width, in different parts of the floor of the warehouse. Furthermore, to calibrate the measurements concrete cores were cut off to measure the actual depth to which the cracks extend. From the instrument calibration it was shown that the measurements taken from instrument appear to be approx. 20% higher than the actual depth of cracks, due to the fact that the cracks that were measured, were not strictly perpendicular to the surface and the existence of neighboring micro-cracks that had further reduced the speed of the ultrasonic pulse. Indicatively, some crack depth measurements are presented in Table 1.

The results show that cracks thickness exceeding 0.2 mm are still at a depth greater than 5.0 cm and cannot be considered as shallow. Many of the cracks that show surface width greater than 5.0 mm travel throughout the thickness of concrete floor.

Concerning the measurements that no reading is shown, this is because the crack posed a through the thickness discontinuity and no wave propagation was possible between the transmitter and the receiver.

Table 1
Crack depth using ultrasonic.

Nos.	Surface crack width (mm)	Reading (mm)	Correction factor	Correct reading (mm)
1	0.1	10.0	0.833	8.0
2	0.2	35.0	0.833	29.0
3	0.3	71.0	0.833	59.0
4	0.5	135.0	0.833	112.0
5	0.8	186.0	0.833	155.0
6	1.0	166.0	0.833	138.0
7	2.0	188.0	0.833	157.0
8	5.0	205.0	0.833	171.0
9	10.0	212.0	0.833	177.0
10	>10.0	–[a]	0.833	–[a]

[a] No readings due to the crack travel throughout the thickness of concrete.

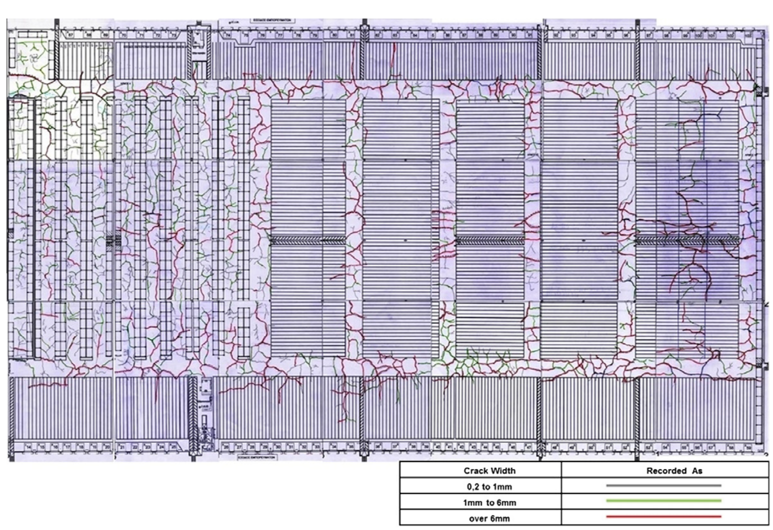

Fig. 4. Main area of the warehouse (around 25,000 m^2 divided into 21 slabs) with recorded cracks.

3.2. Investigation of voids existence between floor and sub-base

To find areas with gaps between the concrete and sub-base or reduced thickness of concrete or internal defects, the average mobility and voids index diagrams of Impulse-Response method were used. Evaluating the results of the process and cutting concrete cores at representative points, revealed the following:

In areas with very high average mobility values (over 25) and displayed as red color in the diagram, there is reduced thickness of concrete (less than 15 cm) and internal discontinuities.

In areas with high average mobility values (15–25) and displayed in red, there is reduced concrete thickness (15–17 cm), confirmed by core sampling. In areas with lower average mobility, no significant damage was detected.

Areas with high rates voids index (greater than 2.5), show a gap between concrete and substrate in the order of 2 mm or more that was confirmed by core sampling.

Indicative results are presented from two corridors (Figs. 5 and 6) and the waveforms of indicative characteristic points. As an example, the difference in voids index (the ratio between the width of the initial maximum mobility to the value of the average mobility) is clearly seen comparing the waveforms of position 4-2 over a confirmed void and position 12-2 which was quite healthy, in Fig. 6.

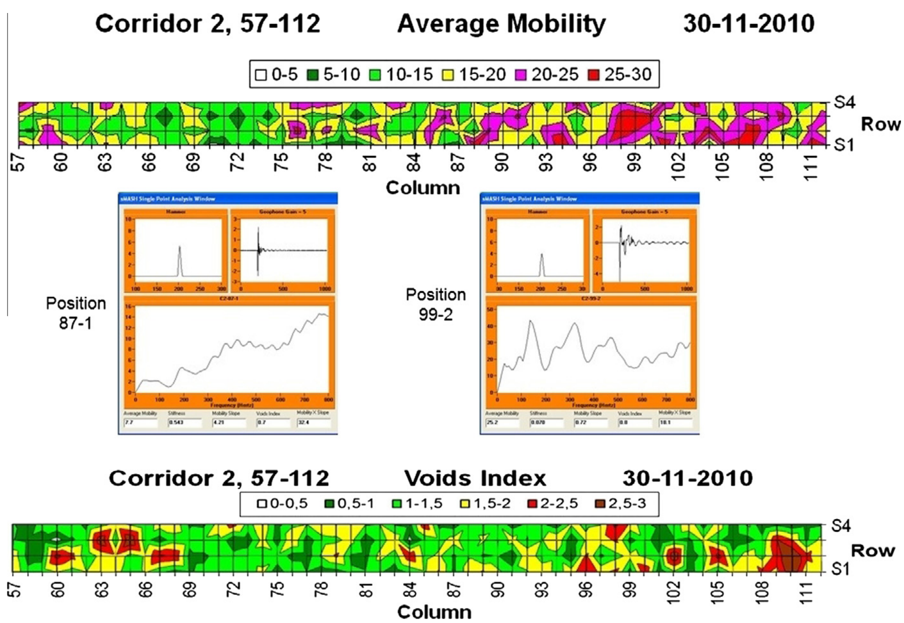

Fig. 5. Average mobility and voids index results (corridor 2).

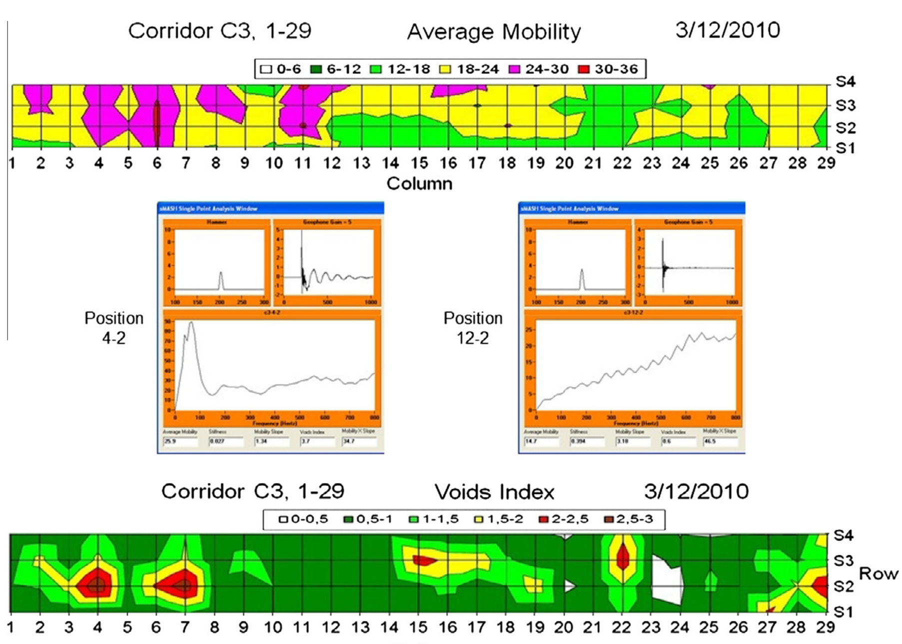

Fig. 6. Average mobility and voids index results (corridor 3).

Table 2
Results of average thickness measurement using Impact Echo Method for different corridors.

Corridor C1 Avg. Thickness (mm)	Corridor C2 Avg. Thickness (mm)	Corridor C5 Avg. Thickness (mm)
174	156	161
Corridor C12 Avg. Thickness (mm)		Corridor C16 Avg. Thickness (mm)
169		162

3.3. Determination of concrete thickness

The concrete thickness was measured, using the Impact-Echo method at points that correspond to axes of the grid that was created during Impulse-Response method testing.

The measurements were made in five corridors of the warehouse (10 measurements at each corridor) and the average values are shown in Table 2.

From all these measurements it was found that the thickness of the floor is at all tested points, less than the thickness defined in the study design (180 mm).

4. Repair

The deterioration of the floor's condition was due to a combination of different decaying processes. The initiation of cracks was due to shrinkage cracking of the early age concrete at the time of manufacturing. These cracks – and more likely new ones – propagated by extensive bending moments due to the reduced thickness and the locally un-compacted base. As the plate was deformed and cracked by bending the gaps between the plate and the substrate were increased leading to further instability, which extended the appearance of cracks due to improper seating of the plate. Based on the observations and the sources of the floor pathogenesis the following repair methods were selected.

The repair method that was chosen included grout injection in order to fill the the voids between the concrete slab and the underlying aggregate layer, while strengthening the sub-base and sealing of the cracks.

The injections were executed in a grid that was designed for this purpose (Fig. 7) and were monitored using the Impulse-Response method. Specifically, a triangular grid was designed, with side dimension of 1.60 m and holes of 26 mm diameter were drilled up to a depth of around 20–22 cm. The reference point was the point A1, which was placed at a distance of 0.5 m from each joint and the injecting grid, as well as the Impulse-Response method testing grid were based on that.

The primary grid was designed prior to the execution of the repair works and was dependent on standard positions of the slab, in order to secure the same grid for the holes and the test positions with the impulse-response method. The drilling and testing positions were marked on the floor. The secondary grid was designed on site to treat areas that appeared to still have voids. The secondary grid was dependent to the holes of the primary grid at certain areas.

The holes were then thoroughly cleaned for dust and debris using compressed air and were injected with grout. The grout used had a W/C ratio of 0.7–0.9 (under pressure of 2 bars at the maximum) and was injected through the drilled holes using equipment specifically designed according to the needs of the project. The injection at each hole continued until the pressured exceded the 2bar limit.

For the production and pressing of the grout, a B1E3 type pressing machine, from the BUNKER company was used. The pressing machine was operating outside the warehouse and the grout was promoted through heavy duty rubber tubing.

For safety reasons the machine was equipped with a 6 bar mechanical valve (grout recycling) and safe shutdown (relay) connected to an oil pressure gauge.

The nozzle that was used for injecting the grout was designed and assembled to facilitate the operator and to be safe against the development of high pressure. It was equipped, as shown below, to supply a control valve (1), a 3 bar mechanical valve (2), an oil pressure gauge (3) and a special nozzle connector (4) with the grout intake system in the floor (packers and tappers, detail, Fig. 8). The intake system consisted of metal packers and plastic tappers from the German company Desoi. The packers' dimensions were ∅25 × 200 mm, with a free-flow diameter of ∅9 mm.

The area, where the injections took place, was inspected using the Impulse-Response method, considering the voids index results, using a 22 × 44 grid, with half the testing positions common with

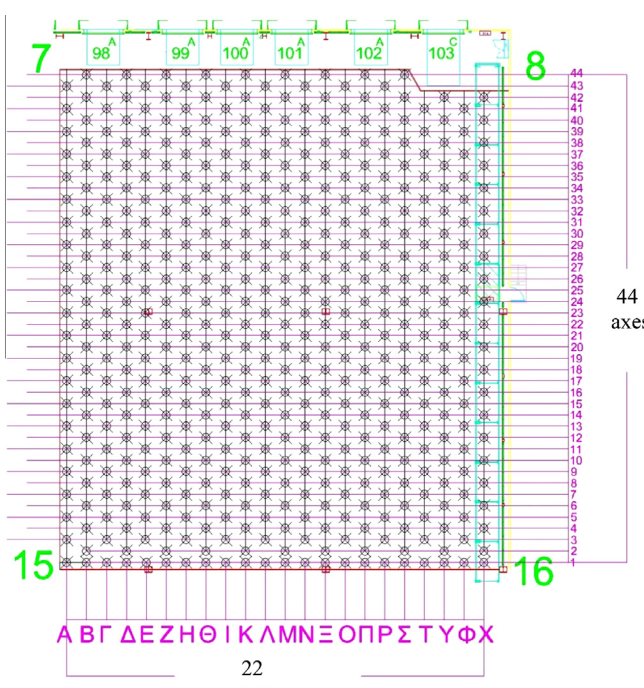

Fig. 7. Injection (points) and Impulse-Response testing (points and line junctions) grid.

Fig. 8. Grout injection nozzle.

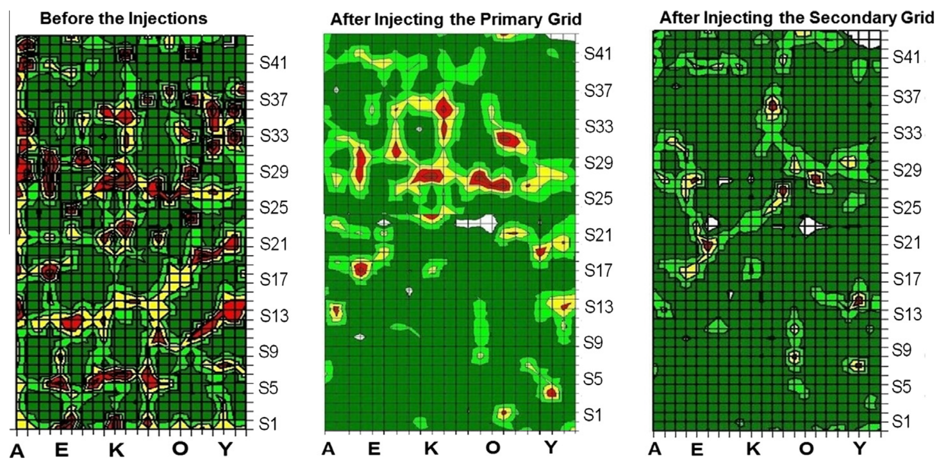

Fig. 9. Graph presentation of voids index results from the inspections of the repair using the Impulse-Response method.

Table 3
Voids index results of the inspections using the Impulse-Response method.

Voids index	Before the injections		After injecting the primary grid		After injecting the secondary grid	
	Number of points	Percentage (%)	Number of points	Percentage (%)	Number of points	Percentage (%)
0–0.5 0.5–1 1–1.5	691	71.38	857	88.53	921	95.15
1.5–2	154	15.91	78	8.06	38	3.92
2–2.5	81	8.37	24	2.48	6	0.62
>2.5	42	4.34	9	0.93	3	0.31

the injection grid. The inspection took place before the beginning and after the completion of the injections. A secondary grid was designed considering the results of the method. After injecting in the secondary grid, the area was inspected for a third time using the Impulse-Response method in order to confirm the successful filling of the voids. Each area was inspected at least two days after completing the injections, in order for the grout to begin curing.

The holes that were injected were 484 in the primary grid and 232 in the secondary grid. The results of the inspection with the Impulse-Response method are presented in Fig. 9 and in Table 3. It has to be noted that in a total of 968 positions that were tested in the three inspections, before the grout injections 28.62% (277 spots) had voids index over 1.5 and after completing the injection in the secondary grid only 4.85% (47 spots) had voids index over 1.5.

Fig. 10. Concrete core, cut off after the grout injections, with visible grout attachment on the bottom side.

5. Conclusions

The use of NDT testing particularly helped to research and diagnoses the problem. Specifically:

- The use of the Impact-Echo method gave us a clear picture of the thickness of the plate by making numerous measurements across the surface.
- The use of the Impulse-Response method identified gaps between the flooring and sub-base.
- Using the ultrasonic pulse velocity measurements, the depth of cracking was calculated.
- The extensive use of the Impulse-Response method during the repair, increase the efficiency of the work. It has to be noted that after injecting in the primary grid, the voids were filled at around 60% and after using the results of the Impulse-Response method to design the secondary grid, the voids were filled at an 83%, according to the percentage of test positions having a voids index value of over 1.5.

All the results of the NDT testing methods were calibrated by comparison to the examination and compression testing of standard concrete cores.

After the end of the works, the results of the Impulse-Response method were verificated by cutting concrete cores at test positions that had a voids index value over 1.5 that was lowered after the injection, as shown in Fig. 10.

References

[1] Sansalone MJ, Streett WB. Impact-echo nondestructive evaluation of concrete and masonry. Ithaca (NY): Bullbrier Press; 1997.

[2] ASTM C1740-10. Standard practice for evaluating the condition of concrete plates using the impulse-response method.
[3] ASTM C1383-04(2010). Standard test method for measuring the P-wave speed and the thickness of concrete plates using the impact-echo method.
[4] ASTM C597-09. Standard test method for pulse velocity through concrete.
[5] Davis AG. Industrial floors on ground, DTI. Copenhagen: Testing of structures NDT-Methods; 2002.
[6] Zoidis N, Tatsis E, Vlachopoulos C, Clausen JS, Matikas TE, Aggelis DG, et al. Visual inspection and evaluation using NDT testing methods of extensively cracked concrete floor Emerging Technologies in Non-Destructive Testing V. In: Proceedings of the 5th conference on emerging technologies in NDT, Ioannina, Greece, September 2011. p. 503–7.