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ULTRASONIC TOMOGRAPHY,
A NON-DESTRUCTIVE MEASURING TECHNIQUE FOR ANALYSIS OF CONCRETE ROADS.

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INTRODUCTION

Quality control of new concrete pavements typically requires destructive sampling in order to verify concrete thickness and material strength. This sampling consists of taking cores from the pavement at a set interval (Figure 1). The practice of taking concrete cores for thickness variation is destructive, expensive and does not adequately characterize thickness variation in concrete pavements (Vancura et al., 2012). If local variations go unnoticed, the pavement may not provide the desired performance during its intended design life. In addition, during the service life of the pavement, there is also a need for regular condition assessment in order to ensure traffic safety and cost-effective maintenance practice. Evaluation efforts mainly verify the presence of (subsurface) distresses in existing pavements to assist in forecasting residual pavement life and make decisions about maintenance, repairs and/or reconstruction.

Figure 1: Current method of core drilling for quality control and assessment of concrete pavements

Non-destructive testing (NDT) permits to assess the quality of new or existing pavements without causing pavement damage. Because of the inherent non-destructive nature of the tests, many data can be collected in order to determine compliance with specifications in terms of concrete quality, thickness and the condition of defects (Sharp and Ozyildirim, 2014). However, traditional non-destructive testing techniques for concrete such as the impact-echo method (Figure 2) have showed reduced accuracy and reliability issues due to the heterogeneity of the concrete matrix (Edwards and Mason, 2011).

Figure 2: Non-destructive impact-echo method (Edwards and Mason, 2011)

Ultrasonic tomography is an emerging NDT technique that shows great promise for quality assurance and quality control. The recently developed ultrasonic tomography device (MIRA^{TM}) was shown to be capable of determining concrete pavement thickness and reinforcement location with increased precision (Hoegh et al., 2011). It can also be used to assess several key characteristics of new as well as existing concrete pavements, including the position of reinforcement, the presence of large cracks or impurities, and concrete homogeneity (Schabowicz, 2014). Studies by the Federal Institute for Material Research and Testing (BAM) in Germany have shown that the system is capable of detecting deep delamination at 203 mm below the surface (Shokouhi et al., 2011).

In this perspective and based on first experiences of researchers at the University of Minnesota (Hoegh et al., 2011), the Belgian Road Research Centre acquired an ultrasonic tomography device of the type MIRA^{TM} in 2013. A second device, the Pundit$^{®}$ PL200-PE, was acquired at the end of 2014.

In a first part of this paper, the global principles of ultrasonic tomography are presented. Subsequently, examples of calibration measurements done on several concrete slabs constructed in the lab are discussed. After this calibration in the lab, thickness measurements were performed on site, the results of which are analyzed in a third part. In the fourth and last paragraph, the usefulness of this method for pavement management is shown by some particular measuring campaigns carried out in Belgium.

1. ULTRASONIC TOMOGRAPHY: A NON-DESTRUCTIVE MEASURING TECHNIQUE

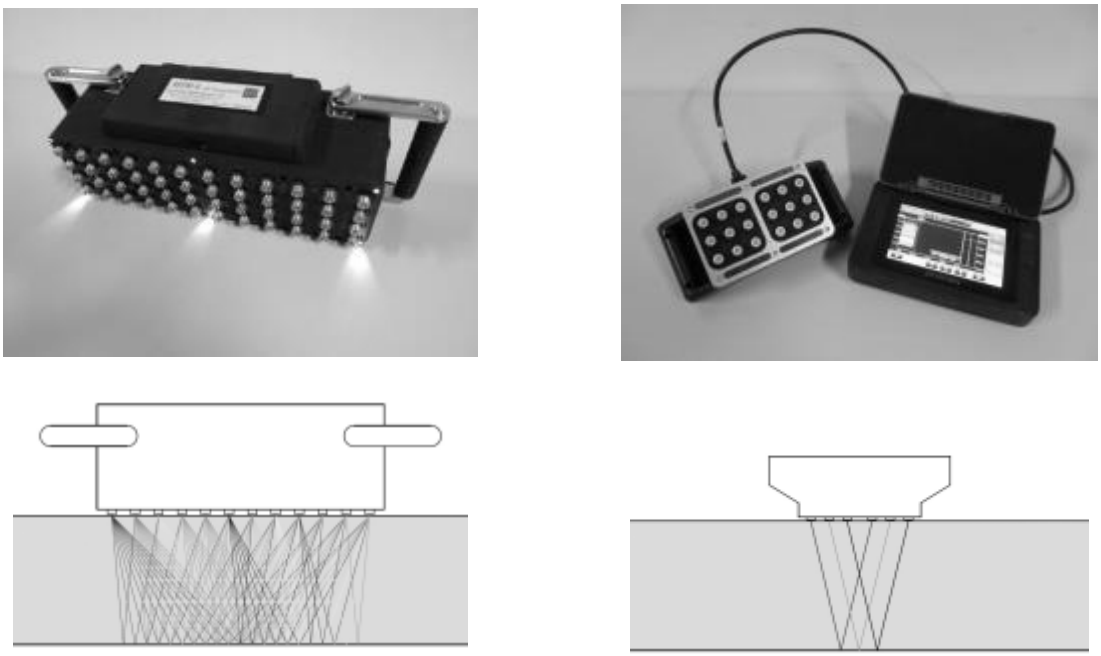
1.1 PRINCIPLE OF ULTRASONIC TOMOGRAPHY

Conventional acoustic methods use the propagation of acoustic waves to characterize the properties and assess the quality of materials. Sound waves which are generated by transducers, are sent into the material and are reflected at each interface between materials of different acoustic impedance. Analysis of the reflected signal provides information about the material through which the signal has propagated.

However, the conventional elastic wave based methods have experienced inconsistent results when applied to materials such as concrete due to the heterogeneity caused by the presence of aggregates, pores and cracks (Schubert and Köhler, 2001). Dry point contact (DPC) ultrasonic array technology provides an opportunity to mitigate the issues caused by the heterogenic nature of concrete by using an array of sending and receiving transducer pairs at set spacing. Traditional ultrasonic methods require a time consuming liquid to couple the transducer to the testing medium. DPC transducers eliminate the need for special surface preparation, and provide the necessary consistency of impact and wave front penetration. The transducer produces an oscillating force over a small contact zone (< 2 mm point source) allowing for a dry contact transfer of the force to the tested medium (Beeldens et al., 2014).

Figure 3 shows the two ultrasonic linear array devices used in this study. The ultrasonic tomography device MIRA™ (Figure 3(a)) consists of a linear array of 48 sending and receiving transducers arranged in 12 channels of 4 transducers. Each channel of 4 transducers sequentially emits shear wave pulses while the other 11 channels receive the reflections from internal interfaces. This allows for 66 separate transmitting and receiving transducer pair measurements per scan. The Pundit® PL-200PE device (Figure 3(b)) uses an array of 9 sending and 9 receiving transducers, utilizing 3 pair measurements per scan.

Both these ultrasonic tomography devices used in current study use the “time-of-flight” measurements between the different transducer pairs for wave velocity calibration within the material, and use the synthetic aperture focusing technique (SAFT) to reconstruct a visual representation of the cross section below the scanned area (MIRA™, 2012; Pundit® PL-200PE, 2014).

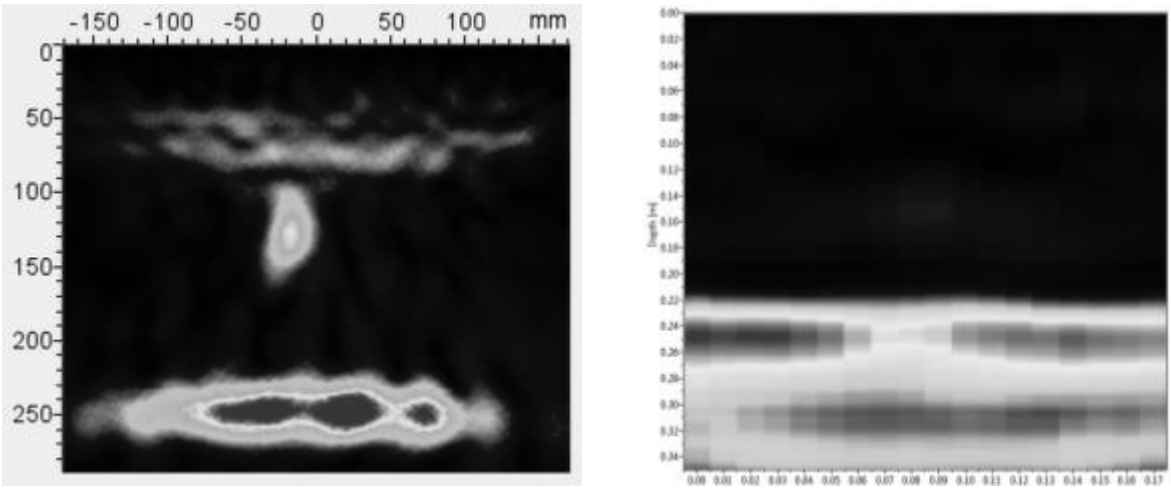


(a) (b)

Figure 3: (a) MIRA™ device; (b) Pundit® PL-200PE device

1.2 EXAMPLE RESULT

Figure 4(a) gives an example scan made by the MIRA™ taken on a concrete pavement with a design thickness of 250 mm. At a depth of 125 mm a reinforcement bar (Ø20 mm) is visible. At a depth of 250 mm, an oblong reflection is visible, which reflects the interface between the concrete pavement and the base layer. Figure 4(b) shows a visual reconstruction made by the Pundit® PL-200PE on the exact same location. The reconstruction is a result of multiple overlapping scans taken in 10 mm step sizes after they have been fused together by the device. On the scan, a high intensity reflection can be observed at the approximate depth of the pavement (250 mm). However, in this case no clear reflection is visible at the place where the reinforcement is located.



(a) (b)

Figure 4: Example of (a) MIRA™ scan; (b) Pundit® PL-200PE scan

2. EQUIPMENT CALIBRATION FOR FIELD USE

2.1 CONSTRUCTION OF LABORATORY SPECIMENS

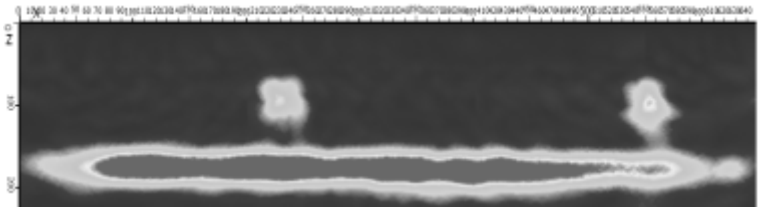
Both the MIRA™ and Pundit® PL-200PE require a parameter setting before performing the actual measurements. Both devices have a different set of variables that can be adjusted in order to improve accuracy of the device. The wave velocity used for SAFT reconstruction can be estimated by both tomographs. In order to determine the accuracy of the default recommended settings and of the wave velocity estimation by the device itself, six concrete slabs were constructed at the premises of the BRRC. Three slabs with a thickness of 180 mm and three with a thickness of 250 mm were constructed. Two of the slabs contained different (artificially created) air-filled voids at various depths below the surface, with one of the two slabs also including a 40 mm thick extruded polystyrene board. Two other specimens contained two reinforcement bars of 20 mm diameter. The specimen thickness, reinforcement type and designed flaws are described in Table 1.

Table 1: Description of laboratory specimens for equipment calibration

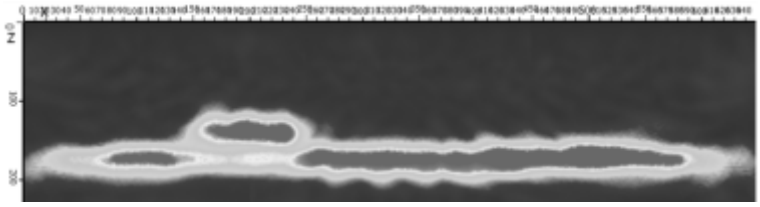
Specimen name	Specimen thickness (mm)	Reinforcement	Defects
A	180	None	None
B	250	None	None
C	180	2 rebars Ø20 mm	None
D	250	2 rebars Ø20 mm	None
E	180	None	2 air-filled voids at the bottom of the slab (size of defects: 25 mm and 40 mm)
F	250	None	Air-filled void (plastic tube with Ø50mm) and polystyrene board (thickness: 40 mm) at a depth of 105 mm

2.2 RESULTS FOR REINFORCEMENT AND SIMULATED DEFECT EVALUATION

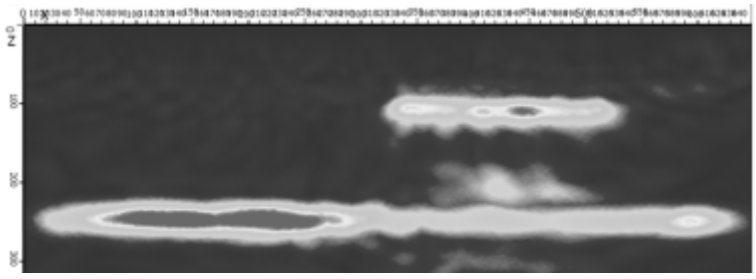
Specimens C through F were analysed using MIRA™ and Pundit® PL-200PE. MIRA™ device could clearly position the reinforcement bars and all of the simulated defects. Figure 5(a) shows a typical scans for the specimen with reinforcement. The scan representatively depicts the position of the reinforcement bars. Figure 5(b) shows specimen E, with a clear indication of the presence of an air-filled void at the bottom of the slab. Figure 5(c) shows specimen F, where the polystyrene board can be detected. For the simulated flaws, not only the position but also the size of the different defects can be clearly distinguished.



(a)



(b)



(c)

Figure 5: MIRA^{TM} scans of different laboratory specimens
(a): specimen C; (b): specimen E; (c): specimen F

Scans made by the Pundit® PL-200PE device does not clearly depict the reinforcement bars, nor the small defect (size = 25 mm) at the bottom of specimen E. The other three designed flaws: the air-filled void with size 40 mm at the bottom of specimen E, the polystyrene board (Figure 6) and the air-filled void with Ø50 mm in specimen F are visible on the scans. However, due to the limited amount of pair measurements used per scan, it is not possible to determine the exact position or the size of the defects.

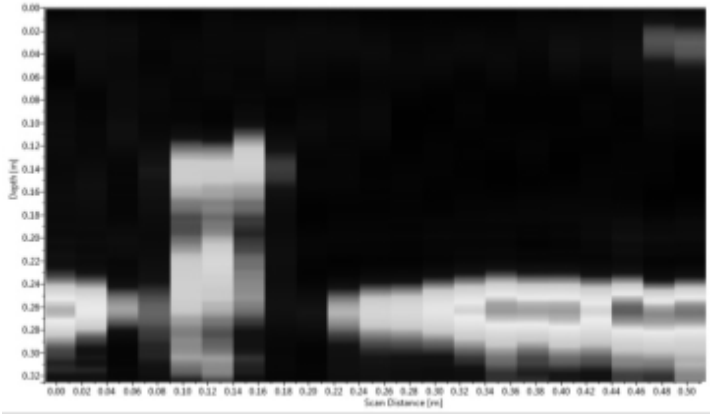


Figure 6: Pundit® PL-200PE scan of specimen F

3. THICKNESS MEASUREMENTS

3.1 CRCP THICKNESS MEASUREMENTS ON THE MOTORWAY E17

The calibration of the MIRA^{TM} device was not only done on the test specimens constructed at the premises of the BRRC, but also on site. One of the first field experiments conducted by the BRRC was done on the motorway E17, a continuously reinforced concrete pavement (CRCP) with an asphalt interlayer of 50 mm between the pavement and the lean concrete base layer. Along the motorway, 27 measurements were conducted in the proximity of locations where cores had to be drilled. Figure 7 shows actual core measured thicknesses versus the thickness measured by the MIRA^{TM}. Due to the fact that this was one of the first experiments done with the MIRA^{TM}, equipment parameters were not yet optimal. Despite this fact, both types of measurements gave a relatively good result with a mean absolute difference of 0.43 cm (with a maximum of 0.93 cm) and a relative thickness deviation range from 0.11 to 4.17% with an average of 1.85% (see Table 2). These differences are similar to the standard deviation within the thickness measured on the cores.

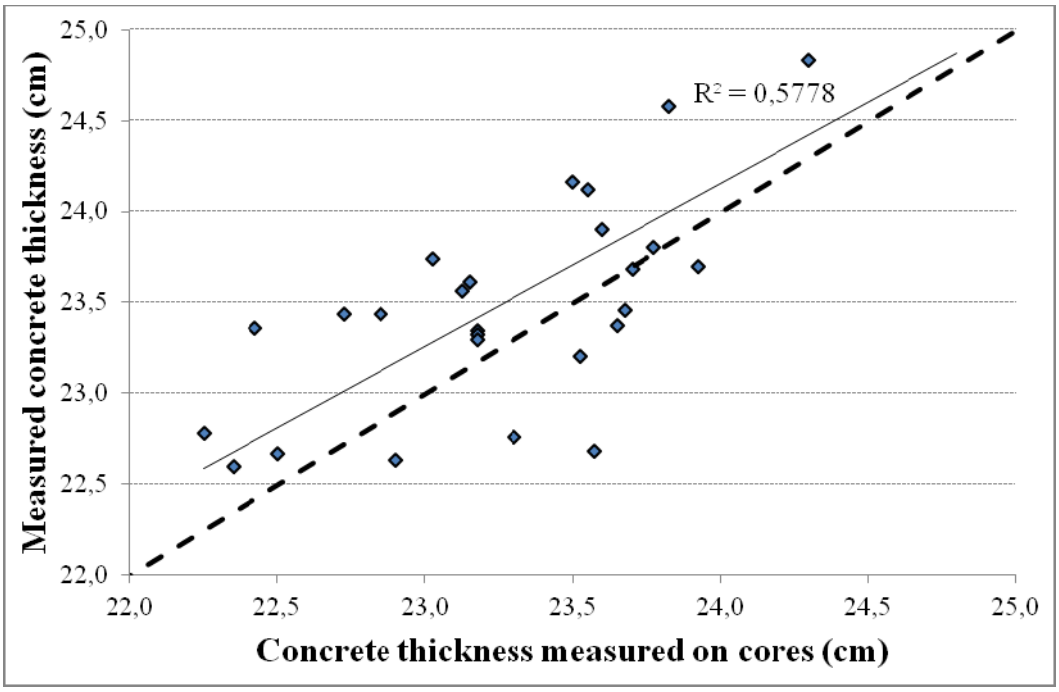


Figure 7: MIRA versus core measured thickness on the motorway E17

Table 2: CRCP thickness measurements on the motorway E17

	Core thickness (cm)	MIRA thickness (cm)	Relative deviation (%)
Average (n = 27)	23.32	23.54	1.85
Standard deviation	0.59	0.70	1.14

3.2 JPCP THICKNESS MEASUREMENTS ON THE 'TERVUURSESTEENWEG' IN ELEWIJT

Another field trial was conducted on the Tervuursesteenweg in Elewijt, a bicycle path in jointed plain concrete. At 15 different locations along the bicycle lane, MIRA™ results were compared versus actual core thickness (Figure 8). As it can be seen, the bicycle lane had a very high variability in concrete thickness. Despite this, a good agreement (R^2 = 0.9749) and accuracy (slope = 0.9949) can be observed between MIRA measurements and the actual thicknesses measured on cores. However, a systematic error of 5 mm seems to be present in the measurements. Further optimisation of the measurement method should avoid this in the future.

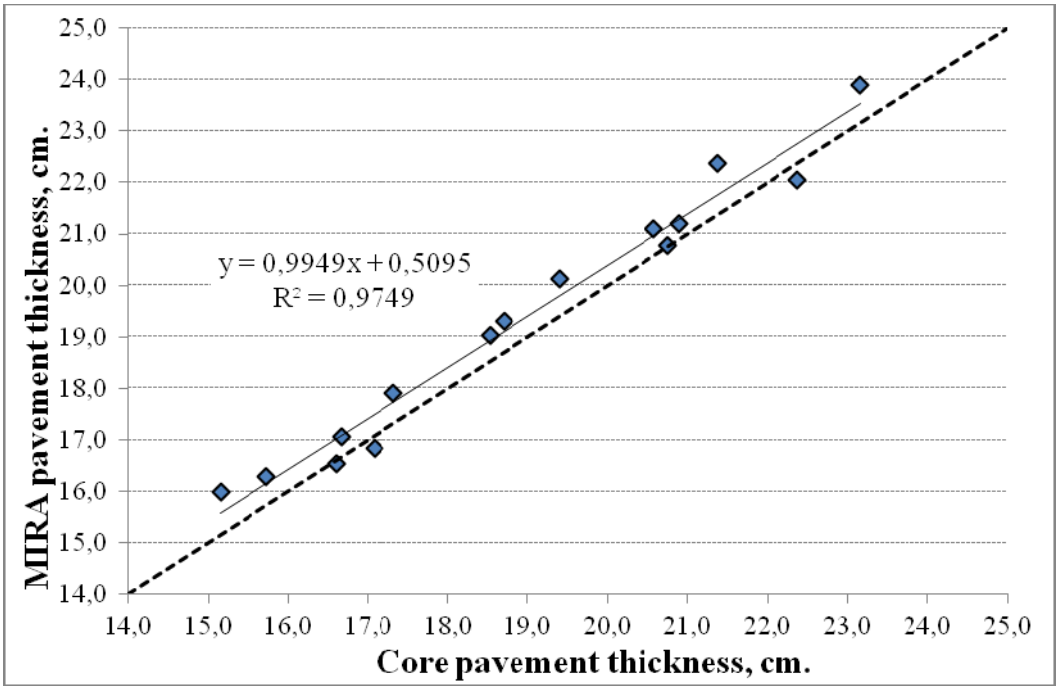


Figure 8: MIRA versus core measured thickness on the 'Tervuursesteenweg' in Elewijt

4. FIELD TRIALS

4.1 LONGITUDINAL JOINT WIDENING ON THE MOTORWAY E34

On the motorway E34 in Assenede, a one lift CRCP was constructed in 2007, following the typical Belgian CRCP design: 230 mm CRCP on an asphalt interlayer of 50 mm and a lean concrete base layer. The slow traffic lane and the emergency shoulder were placed in phase 1, while the left lane was constructed in a second phase. For the longitudinal joint, a classic keyed construction joint was put in place with tie-bars. At a certain point, due to problems with the automatic tie-bar insertion, tie-bars had to be inserted manually by drilling in the hardened concrete and gluing the tie-bars.

After 7 years in service, a widening of the longitudinal joint was noticed, with joint widths going up to 40 mm at some places. At other places, cracks appeared near the joint, as can be seen on Figure 9. Ultrasonic tomography was used to carefully determine the position of the tie-bars. In addition, cores were drilled to check the condition of the tie-bars and to verify the presence of glue.

Figure 9: Cracking near the longitudinal joint on the motorway E34

Three of the cores are shown in Figure 10. The conclusions were that no or too little glue was used to tie the rebar in the drilling hole. Core 1 was taken in the left lane (second phase). Here, a good bond between the concrete and the tie-bar was visible. Cores 2 and 3 taken from the right lane, did not show any bond between the tie-bar and the concrete. The absence of glue caused the slow traffic lane to shift away, resulting in longitudinal joint widening.

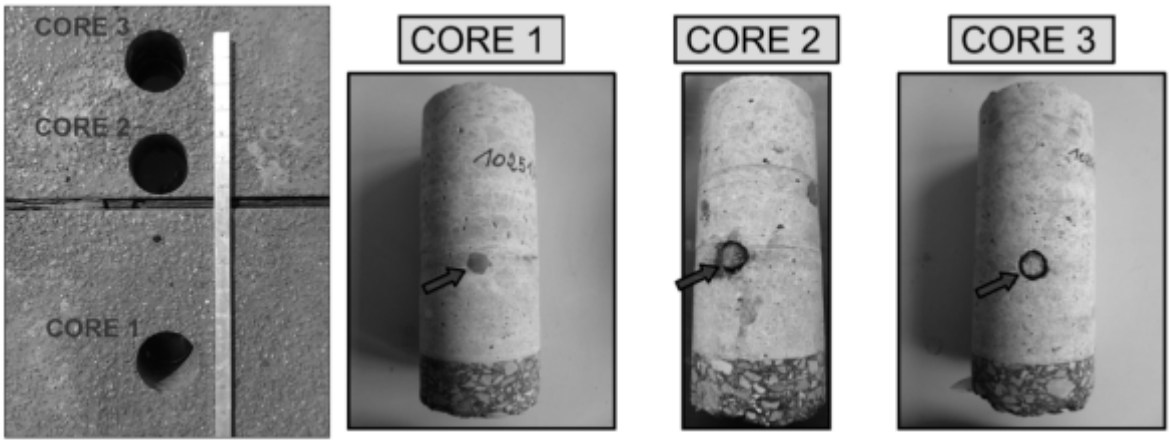
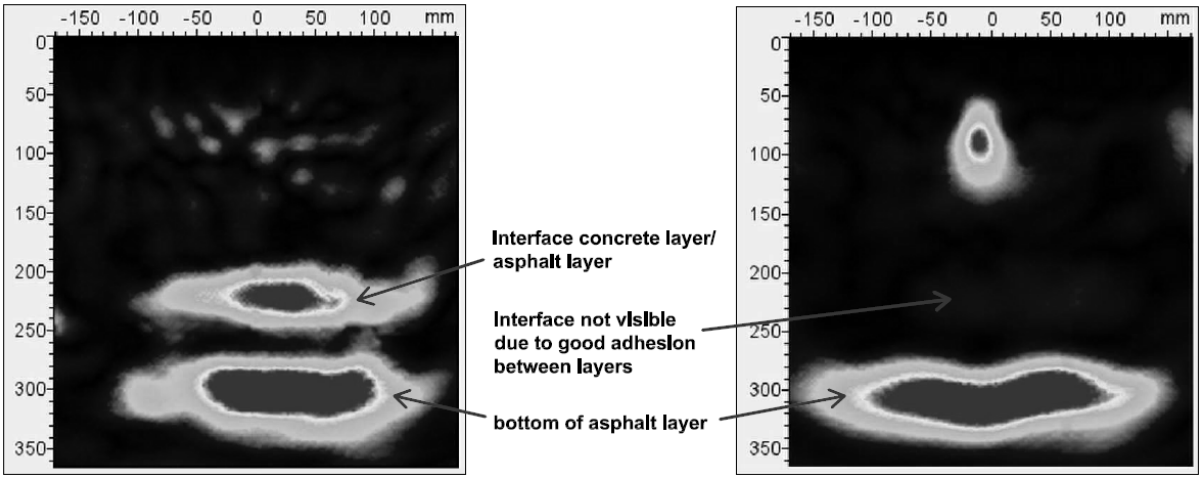


Figure 10: Cores taken over the tie-bar at the longitudinal joint of CRCP (motorway E34)

By interpreting the ultrasonic tomography scans it was also possible to evaluate the bonding between the CRCP and the asphalt interlayer. If cracking or debonding between both layers occurred, a strong oblong reflection would be visible at the depth of the pavement (Figure 11(a)). Where good adhesion between both layers was found, the transition would not be clearly visible on the scans (Figure 11(b)). This could also explain the lower accuracy of the thickness measurement performed on the motorway E17 (see 3.1).



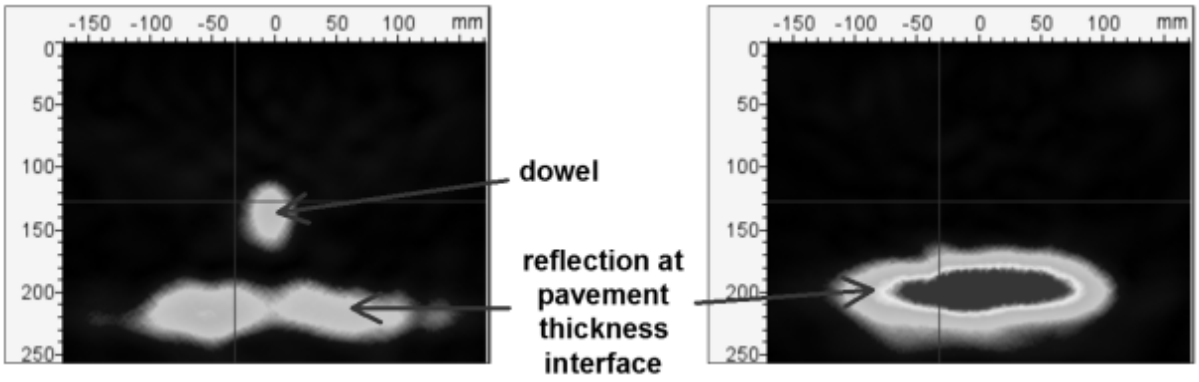
(a) (b)

Figure 11: Evaluation of bonding between concrete pavement and asphalt interlayer; (a) no bonding between both layers; (b) good bonding between both layers.

4.2 FAULTING OF CONCRETE SLABS

Ultrasonic tomography measurements were also conducted on the highway N1 at Braken. On this old JPCP, measurements were taken along the transverse contraction joints to verify the presence of dowels as it was suspected that dowels were not installed correctly at some of the joints.

MIRA^{TM} scans indeed confirmed these suspicions as dowels were only found along some of the joints. In fact, the absence of dowels could be directly linked to the faulting of the slabs. It was also noticed that at locations where no dowels were found, the scans showed a high intensity reflection at the bottom of the pavement, as illustrated in Figure 12. It is suspected that the high intensity reflection results from a cavity right underneath, caused by erosion of the base layer.



(a) (b)

Figure 12: Measurements on the JPCP in Braken to verify the presence of dowels (a) dowel present; (b) absence of dowel

Similar measurements were conducted on the highway R4 near Wachtebeke, Ghent and on the highway N2 in Bekkevoort. During construction of these pavements, the surveyors had noticed that the dowels had shifted. The MIRA^{TM} was used for the evaluation of alignment of the dowel bars. Along several joints, the dowels were carefully detected and positioned. The results showed dowel misalignment along various joints as shown in Figure 13. As a result, both pavements were demolished and reconstructed.

(a) *(b)* *(c)*

Figure 13: (a) and (b) dowel misalignment on the highway R4 near Wachtebeke, Ghent; (c) dowel misalignment on the highway N2 in Bekkevoort.

CONCLUSIONS AND PERSPECTIVES

Ultrasonic tomography is a promising non-destructive measuring technique for the evaluation of concrete thickness, position of reinforcement and presence of cracks and impurities. This technique can be used for quality control and follow-up of new pavements, but also for non-destructive analysis of existing pavements in order to determine the cause and extension of distresses on these pavements.

In this perspective and based on first experiences at the University of Minnesota, the BRRC acquired two ultrasonic tomography devices, a MIRA^{TM} and a Pundit® PL200-PE type. In this study, these two systems were used to evaluate six concrete specimens with reinforcement and simulated defects. The results confirmed the potential of both ultrasonic tomography devices for detecting flaws with a size greater than 40 mm. Only the MIRA^{TM} device could also detect the reinforcement bars and the smaller defect (size = 25 mm).

Additional calibration measurements were performed on continuously reinforced concrete pavements, as well as on jointed slab pavements, to verify the capability of the MIRA^{TM} device to determine concrete pavement thickness. The results confirmed the potential and the accuracy of the ultrasonic tomography thickness measurements compared to core drilling.

In addition, measurements were also performed on concrete pavements in-situ to analyze different types of distresses occurring in the field such as longitudinal joint widening in a CRCP and concrete slab faulting in a JPCP. The results demonstrate the application possibilities and the usefulness of this NDT method for pavement management systems.

Future research will focus on developing a standardized and accurate ultrasonic tomography measuring protocol for concrete pavements. This will increase the accuracy of the measurement technique in the field. Furthermore, the influence of concrete composition and construction method on the ultrasonic wave velocity within the concrete will be investigated. Finally, to improve productivity and objectivity of data interpretation, the processing of the measurement results will have to be optimized.

ACKNOWLEDGEMENTS

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