CONCRETE PAVEMENT JOINT DIAGNOSTICS USING ULTRASONIC TOMOGRAPHY

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ABSTRACT

Proper construction and maintenance of transverse joints in jointed plain concrete pavement is an important issue in extending pavement life. This study presents the capabilities of an ultrasonic tomography device in providing information essential to joint rehabilitation decisions as well as quality control of rehabilitation construction. Testing was conducted at various partial depth repair locations of a recently repaired in-service highway to determine the presence and/or extent of debonding between the partial depth repair and the existing concrete. Testing was also conducted at the Minnesota Road Research Facility to evaluate the subsurface condition along various transverse joints. The real-time diagnosis using the intensity-based synthetic aperture focusing technique signals showed success in pinpointing the location of de-bonded concrete interfaces within partial depth repairs. The ultrasonic tomography testing also showed the capability of identifying that a joint is in need of repair and subsequently diagnosing the extent of subsurface deterioration throughout the joint.

INTRODUCTION

Transverse joints are saw cut into jointed plain concrete pavements (JPCP) to control cracking caused by expansion and contraction of the portland cement concrete (PCC) slab due to temperature and moisture variations in the concrete layer. While dowels are used to improve the performance of such joints by ensuring proper load transfer between the two slabs, the introduction of joints can cause distresses in the pavement due to environmental and wheel loading. Rehabilitation strategies such as partial depth repair can be used to mitigate or repair joint distresses such as spalling at the surface.

Visual inspection is an effective method inspecting transverse joints surface distress. However, visual inspection does not allow for determination of the distress until it manifests at the surface and cannot be used to determine the extent of subsurface damage. Detection of distress prior to surface exposure can be beneficial in improving rehabilitation timing, and determination of subsurface extent can assist in determining the type of rehabilitation (i.e. partial vs. full depth repair). The ability to nondestructively evaluate the quality of the construction and/or repair at the joint (such as verifying a full bond between the repair materials and existing concrete in a partial depth repair) can help in acceptance or rejection of construction or reconstruction. Since all of these issues involving PCC joint evaluation are important factors in increasing service life of the pavement, finding an effective nondestructive method for this application is of significant value.

Non Destructive Testing (NDT) techniques have been used to evaluate concrete pavements joints for many years including ground penetrating radar (GPR), magnetic pulse-induction, chaining, and other seismic methods such as impact echo (IE). Past studies show that GPR is capable of achieving high speed measurements of pavements although the accuracy reduces with higher speeds and detecting non-uniform cracks is difficult (Gucunski et al., 2010.; Gucunski, et al., 2009; Abdallah I. N., 2009; Li et al., 2008; Maierhofer C., 2003; Chong et al., 2003). Magnetic pulse-induction can locate metal inclusions with high accuracy, although it does not detect any type of non-metallic inclusion or defect (Rao et al, 2009; Hoegh et al., 2008; Hossain et al., 2006; Khazanovich, 2003). Infrared thermography can indicate subsurface anomalies such as delamination in concrete, although this method is limited by environmental conditions and depth of the defect (Washer, G. et al., 2009; Clark et al., 2003; Maser et al., 1990). IE has shown the capability of detecting thickness and planar flaws, however non-planar flaws that do not result in resonance can be difficult to detect (Schubert and Köhler, 2001; Carino, 2001; Alexander et al., 2005). Chain dragging is a method currently used extensively by state agencies for PCC joint evaluation among other applications. This method can be effective when the operator is experienced and skilled. However, the analysis is qualitative and does not result in a record of data that can be further analyzed.

This paper explores the use of an ultrasonic tomography device, MIRA, for evaluation of concrete pavement joints. High frequency (greater than 20,000 Hz) sound waves generated by transducers are used to characterize the properties of materials or detect their defects. In the pitch-catch method used in this study, the sound waves are guided into the PCC, and the resulting reflections are analyzed. The dry point contact (DPC) transducers used in this study transmit relatively low frequency (55 khz) shear waves that penetrate the necessary depths for subsurface evaluation of concrete structures (Nesvijski, 1997; Mayer et al., 2008). Use of these transducers has been applied for years in dealing with detailed evaluation of civil structures such as tendon ducts and bridge decks (Schubert and Köhler, 2001; Mayer et al., 2008; Khazanovich et al. 2005; Langenberg, K.J. et al., 2001; Marklein, R. et al. 2002).

Figure 1 shows a manual MIRA measurement on the left which utilizes the 45 transmitting-receiving pairs from the 40 transducer, 10 channel, ultrasonic array, along with the synthetic aperture focusing technique (SAFT) to create a 2 dimensional reconstruction of the concrete directly below where the scan was taken (SAFT B-scan) in approximately 1 second (Hoegh et al., 2011.). On the right side of Figure 1 the 45 measurement pairs utilized in each MIRA scan providing an increased redundancy of information of MIRA (bottom) over conventional IE (top) can be observed.

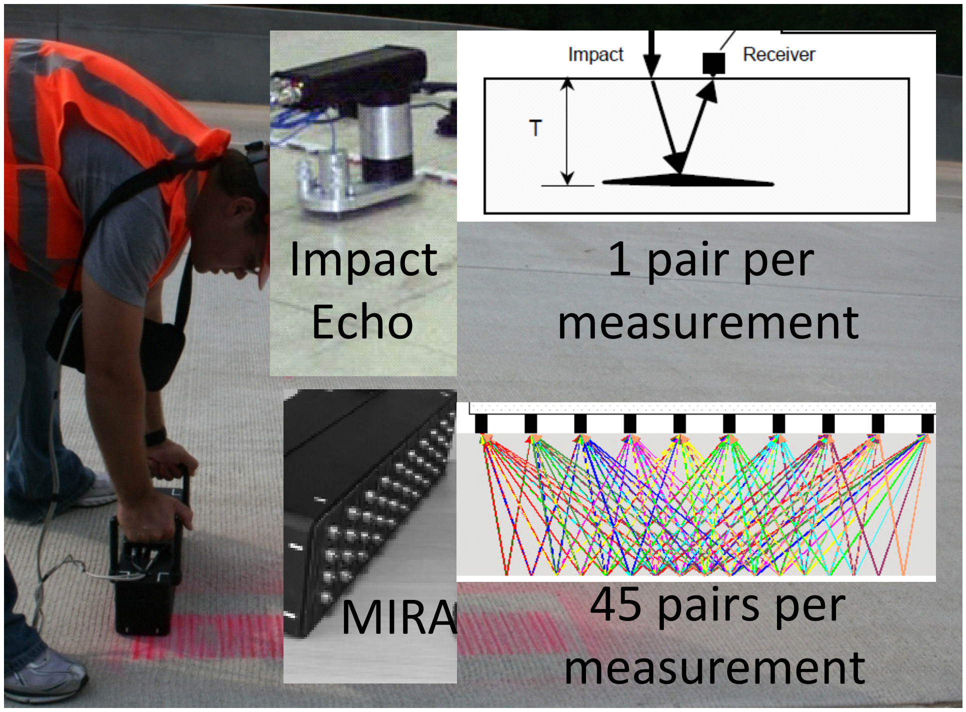

Figure 1. MIRA ultrasonic pitch-catch device and comparison with traditional impact echo method (Carino, 2001; Hoegh et al., 2011).

MEASUREMENT PROCESS AND SIGNAL INTERPRETATION

Each of the 45 transmitting and receiving pairs from the array of transducer channels in each MIRA scan gives intensity versus time information. In order to visualize the subsurface condition below each measurement, the time-of-flight arrivals must be converted to distance. The shear wave velocity used to make this conversion is measured in "calibration mode" by dividing the fixed distance between the transducer pairs by the respective shear horizontal (SH) arrival times. This characteristic SH wave velocity is used in "scan mode" by the synthetic aperture focusing technique (SAFT) to reconstruct the medium below the measurement based on the body shear wave reflections that arrive at the surface. SAFT has been found to be a feasible algorithm for use with the ultrasonic pitch-catch technology as well as other applications (Langenberg et al., 2001, Hoegh et al., 2011). Each approximately 1 second MIRA scan gives a 2 dimensional depth cross-section (SAFT B-scan) with the vertical axis indicating the depth of any reflection (caused by any change in acoustic impedance), and the horizontal axis indicating the location along the aperture of the device with 0 being the center of the scan location.

When evaluating SAFT B-scans, changes in acoustic impedance (affected by material stiffness changes) will cause a high intensity of reflection (red) associated with the location of the anomaly. This method can be used to detect debonding between concrete layers among other subsurface anomalies. Figure 2 shows the result of a MIRA scan taken at a full depth repair location. This example SAFT B-scan indicates little to no reflection (blue) until a high intensity of reflection (red) at a depth of approximately 9 in. (~225 mm) at the interface between the concrete and base material. This type of strong "backwall" reflection at the depth of the concrete and base interface should be expected if there is no significant flaw in a single concrete layer.

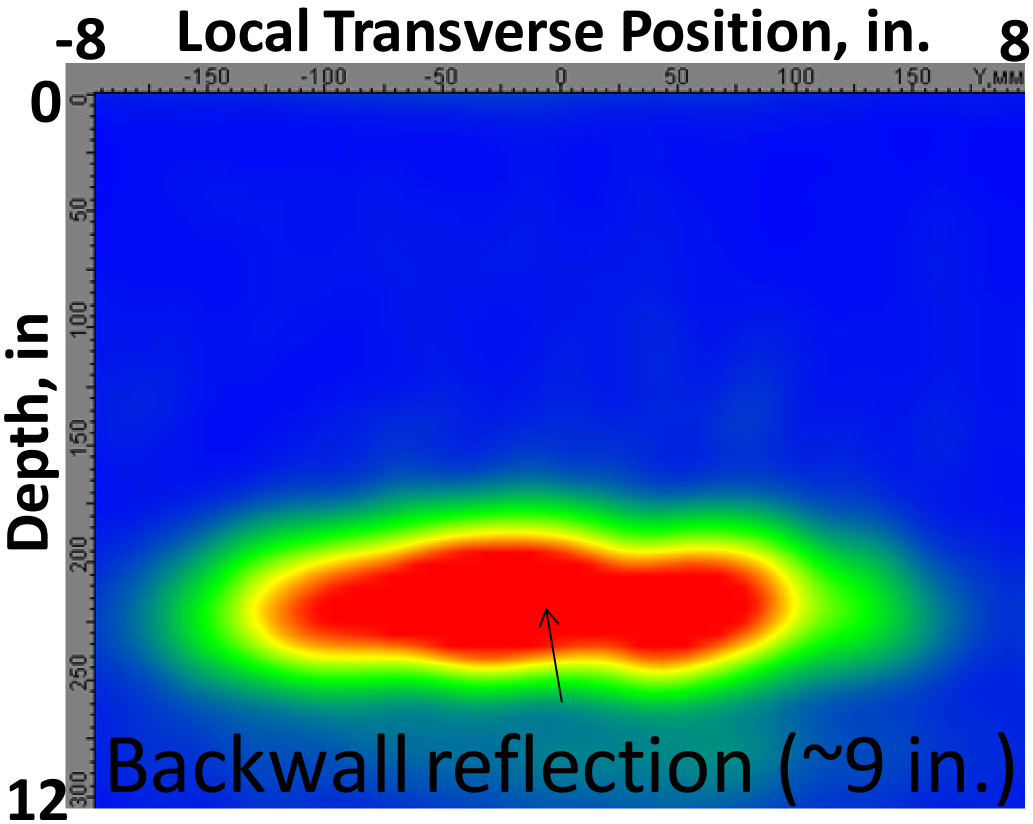

Figure 2. Example B-scan taken at a full depth repair area showing a typical backwall reflection (red) at the interface between the base concrete and base at approximately 225 mm.

It is important to note that this signal is much cleaner (blue with little to no green, yellow, or red at depths above the backwall reflection) than that of even a properly bonded partial depth repair over existing concrete. Figure 3 shows an example B-scan taken at a properly bonded partial depth repair location showing a typical backwall reflection at the interface between the concrete and base as well as some additional lower intensity reflection at shallower depths where the new and old concrete interface is located. These lower intensity reflections are caused by the presence of two different concrete layers with slightly different acoustic impedance as well as coarse aggregate. This was determined through the consistent appearance of moderate intensity reflections in B-scans at the depth of the repair material layer, even in cases where cores verified a proper bond.

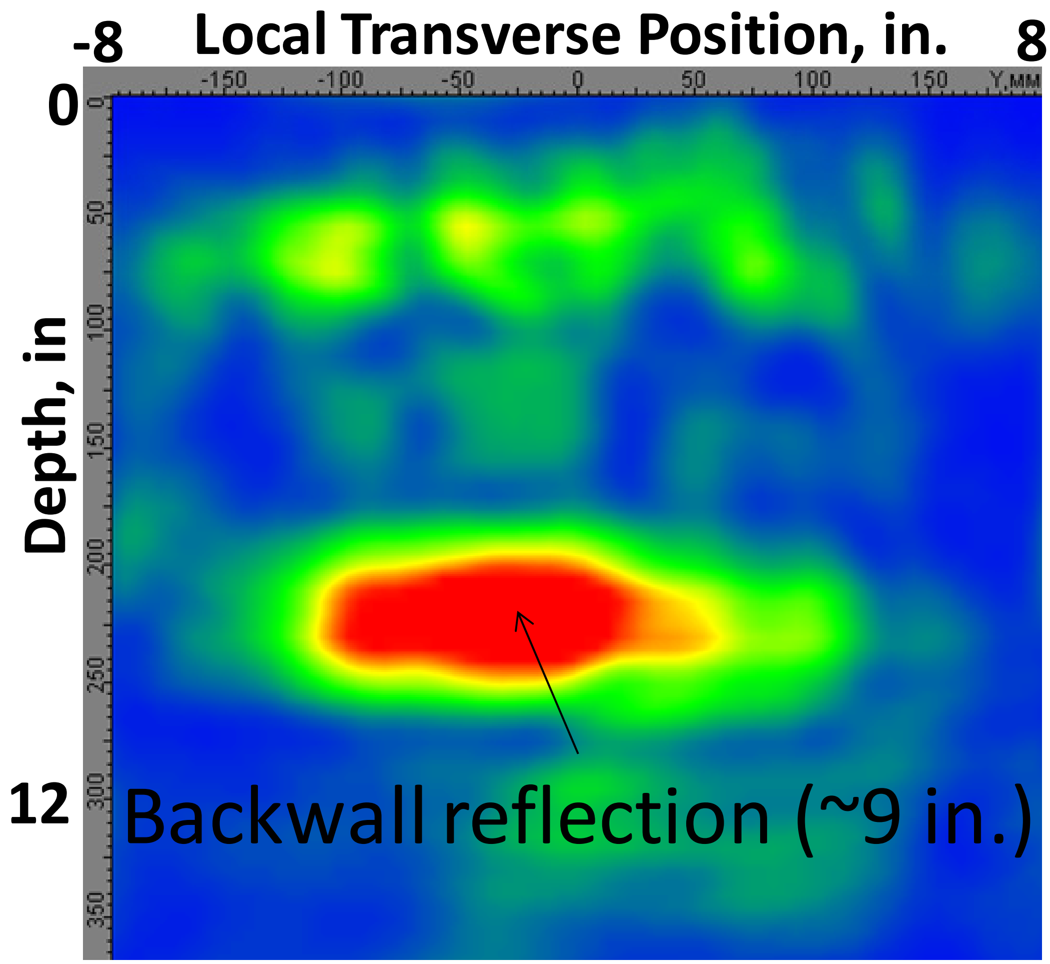

Figure 3. Example B-scan taken at a partial depth repair location where no metal reinforcements are present.

Metal inclusions can also cause reflections of the shear waves. Figure 4 shows an example scan taken at transverse joint indicating the presence of dowels. The high intensity reflections near 4 in. (~100 mm) indicate the presence of dowels. However since the MIRA B-scan uses multiple measurement pairs, the presence of the backwall reflection between the concrete and base is still visible.

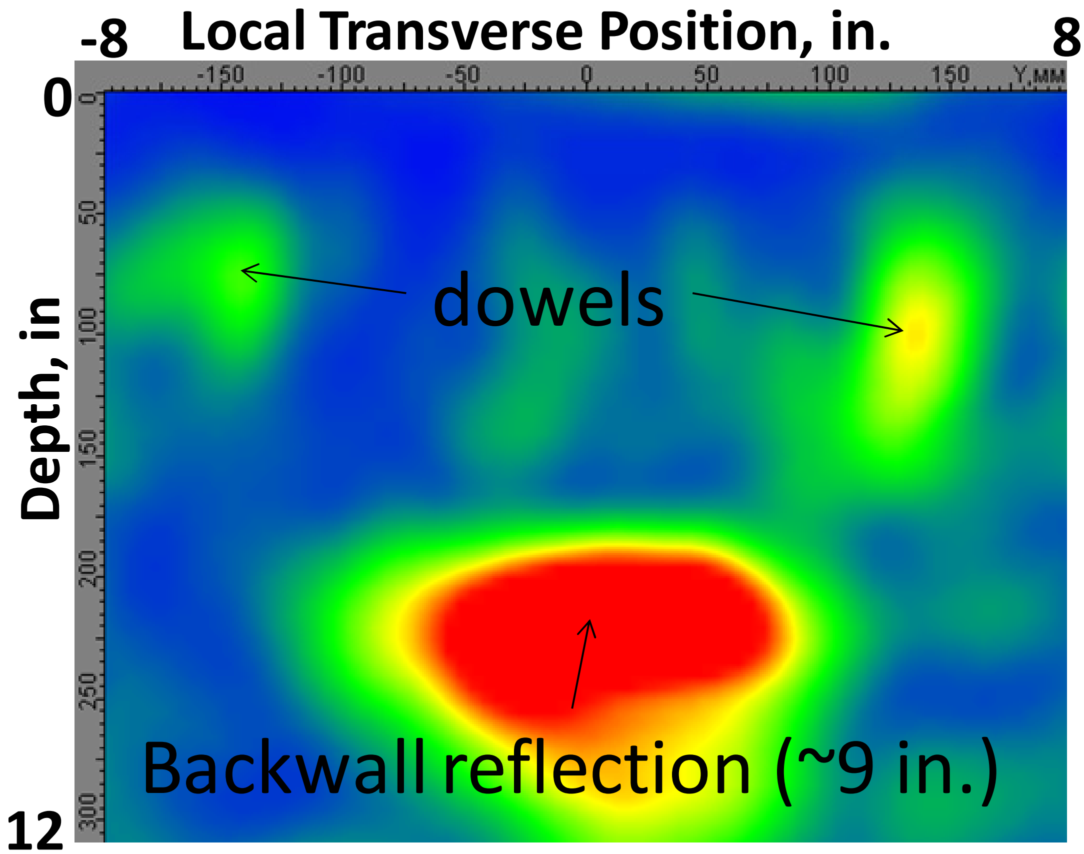

Figure 4. SAFT B-scan taken at a partial depth repair near a transverse joint where dowels are present.

The SAFT B-scans shown in figures 2 through 4 are the type of scans that indicate a sound concrete condition with high intensity reflections only associated with locations of metal dowels (if present) and the depth of the concrete/base interface. Variation from these types of scans can indicate the presence of subsurface damage.

One type of variation from a typical scan that indicates subsurface damage is called shadowing. Shadowing refers to the absence of a high intensity of reflection at a location where there is a change in acoustic impedance. The depth of the interface between the top concrete layer and base is primarily used for the shadowing analysis and this interface will be referred to as the "backwall" in this study. Since there is a large difference in acoustic impedance between the concrete layer and the base layer a high intensity of reflection at this planar depth should be expected. However, if there is an obstruction at a shallower depth, shear waves will either be reflected back to the surface or attenuate before they penetrate to the depth of the backwall. Therefore, since there are 45 transmitting and receiving pairs in each measurement, it can be assumed that there is a planar obstruction such as debonded partial depth repair or deteriorated concrete if a low intensity of reflection is observed at the backwall depth within a SAFT B-scan. This type of analysis is useful for diagnosing the presence or extent of subsurface damage at concrete pavement joints and/or evaluating the quality of rehabilitation construction as will be detailed in the following field trials section.

FIELD TRIALS

Partial Depth Repair

MnDOT personnel allowed for access to in-service highway that was recently rehabilitated at the transverse joints using partial depth repairs. Chaining (the traditional NDT method for this type of diagnostics) was carried out by experienced MnDOT personnel to identify general areas where there was potential debonding. The MIRA ultrasonic tomography scans were also taken to fuse with the chaining information to make decisions on where to take cores. An example partial depth repair section where verification cores were taken illustrates the capabilities of fusing MIRA and chaining for quality assurance of partial depth repair bond with existing concrete. Figure 5 shows a series of MIRA scans (positions 1 through 12) taken at an approximately 2 ft. by 2 ft. partial depth repair located at a transverse joint. The left side of the partial depth repair (shown in) figure 5 is approximately 3 ft from the truck lane fog line.

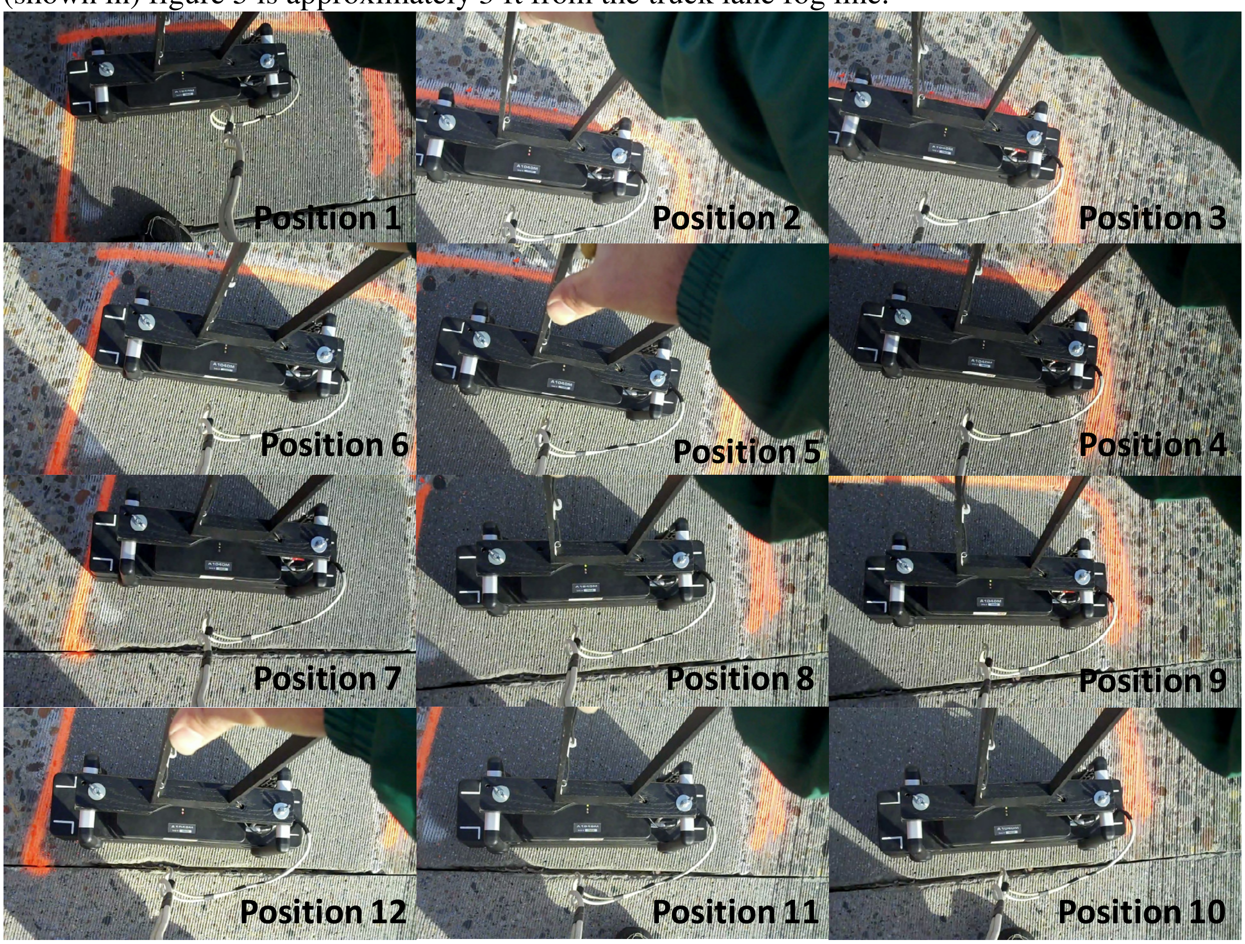

Figure 5. Twelve MIRA scan locations taken at the example partial depth repair.

Each of these scans resulted in real time SAFT B-scan results associated with the condition of the concrete below (shown in Figure 6). It can be observed from Figure 6 that a large majority of these scans experience shadowing (explained in the section above) of the backwall reflection at about 9 in. (~225 mm). This indicated the presence of a planar flaw such as debonding which was corroborated with the chaining information that this general vicinity was experiencing debonding.

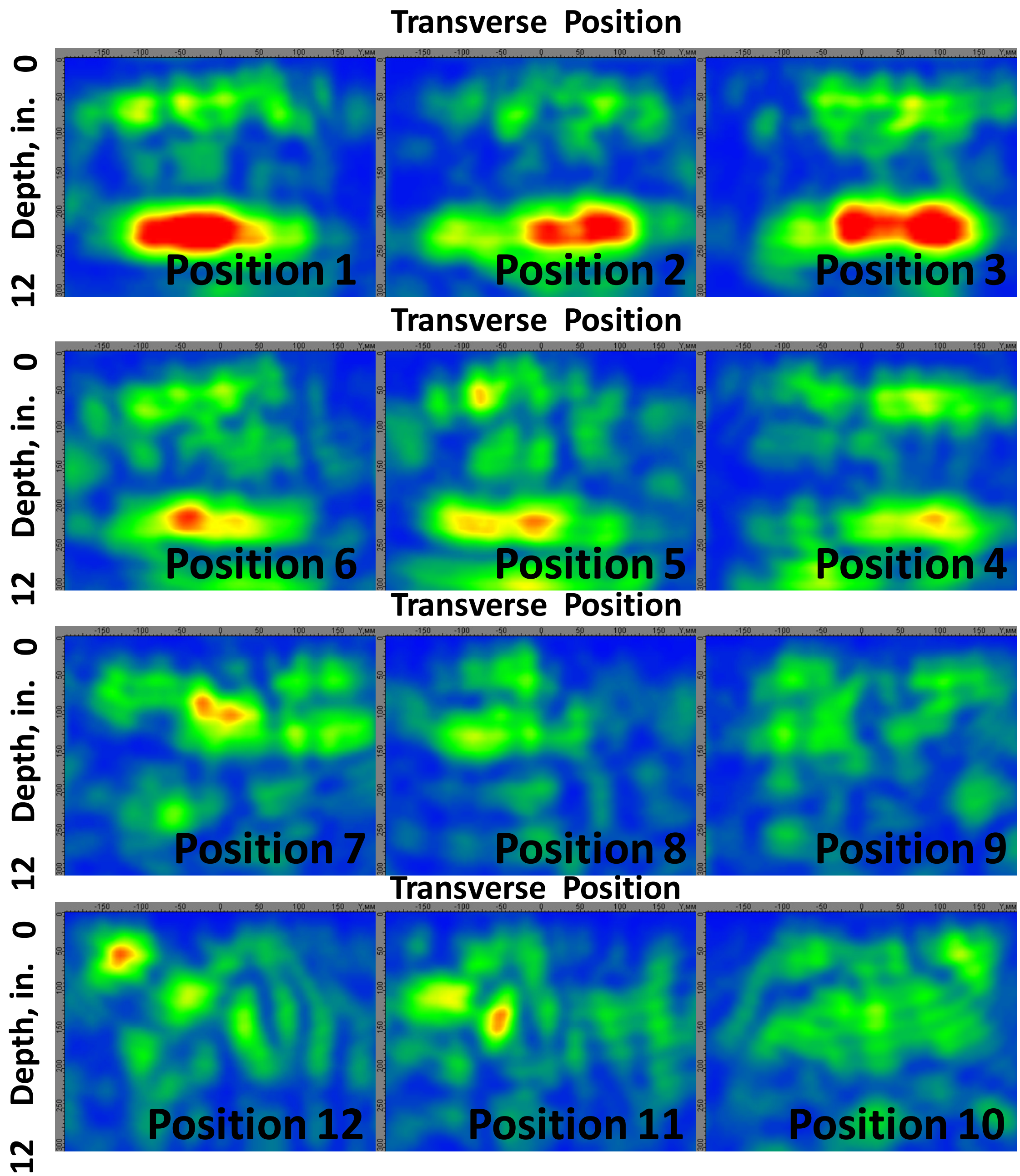

Figure 6. SAFT B-scans associated with the 12 MIRA scan positions shown above (depth of each scan: 300 mm).

Therefore, a core was taken at a location within this partial depth repair (towards the fog line and away from the transverse joint) as shown in Figure 7. The core at this location showed a proper bond between the partial depth repair and the existing concrete upon inspection of the cross-section as shown in Figure 7 on the right.

Figure 7. Core location (left) and result showing properly bonded partial depth repair.

SAFT B-scans within the area deemed to be experiencing debonding were matched with their corresponding positions. Further inspection revealed that a few of the scans in this vicinity did in fact have a strong backwall reflection indicating a proper bond. These scans included the location where the core was taken (positions 1 and 6). Figure 8 shows the position 1 (left) and position 6 (right) scan locations and B-scans. It can be observed that these scans are similar to the example scan shown in Figure 3 which indicates a proper partial depth repair bond. The clear backwall reflection at the concrete and base interface gives the indication of a proper partial depth repair bond above.

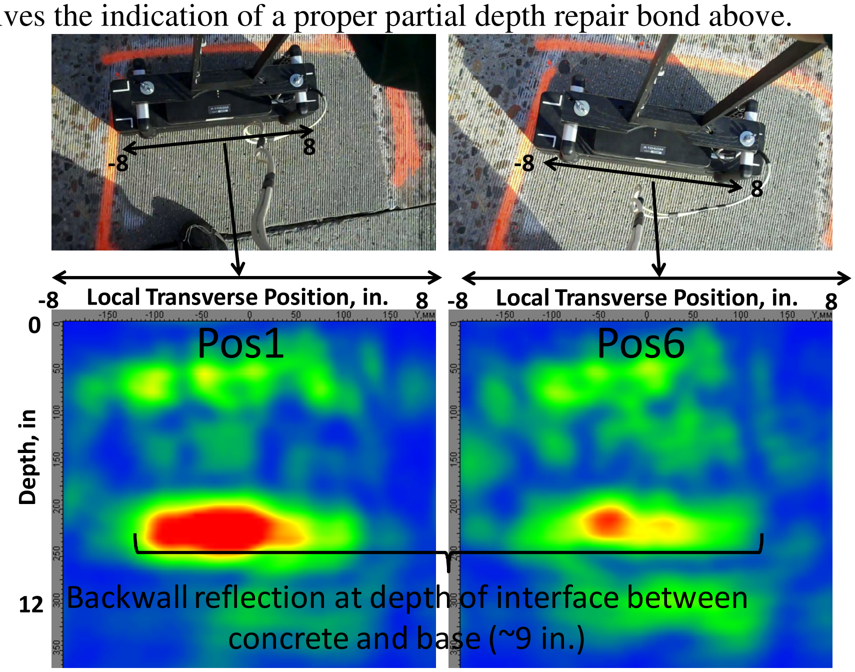

Figure 8. SAFT B-scans in the location where the first core was taken with a strong backwall reflection indicating a proper bond between of the partial depth repair.

Locations where the backwall reflection experienced clear shadowing (positions 8, 9, 10, and 11) were inspected further with MIRA measurements to pinpoint a location where the core would verify the debonding within this general vicinity (positions 9 and 10). Figure 9 shows the position 9 (left) and position 10 (right) MIRA scan locations and associated B-scans. It can be observed that these SAFT B-scans are dissimilar to the type of SAFT B-scan that should be expected for a properly bonded partial depth repair. In these scans the backwall reflection at the depth of the interface between the existing concrete and base layer is not present. This is an indication that the unbounded condition at the partial depth repair interface obstructed the shear waves from through transmission to the depth of the concrete.

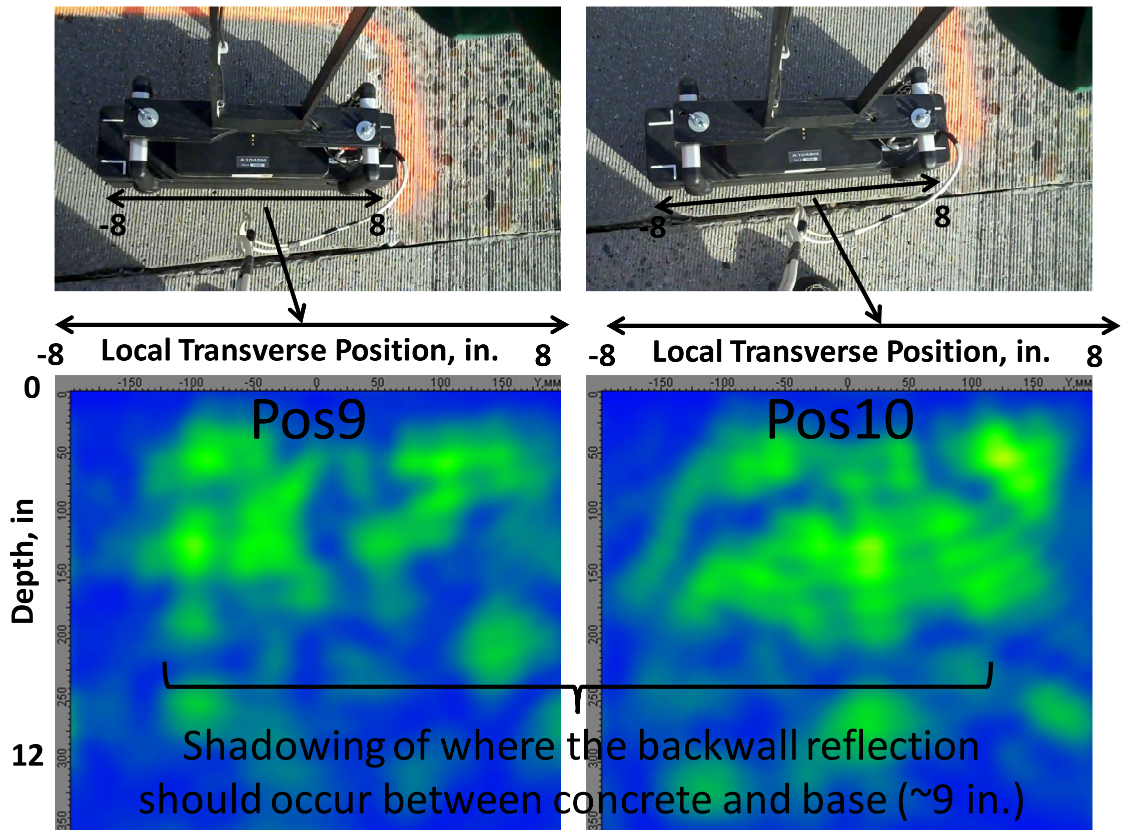

Figure 9. SAFT B-scan locations indicating a poor bond between the partial depth repair and existing concrete.

The core taken using this pinpointed location is shown in Figure 10 (B). It can be observed that the partial depth repair is de-bonded, especially when compared to the properly bonded location core (Figure 10A). This verified the non-destructive diagnosis of an improperly bonded partial depth repair.

(A) **(B)**

Figure 10. Cores taken at the area (B) towards the centerline near the transverse joint indicating an improperly bonded partial depth repair in comparison to (A) the properly bonded repair.

A similar process was used to pinpoint a debonded location in other joint locations where MIRA indicating debonding. Another core verifying debonding of the partial depth repair as indicated by MIRA pinpointing diagnosis is shown in Figure 11.

Figure 11. Core showing debonding of the partial depth repair.

Joint Subsurface Evaluation

A field trial at the Minnesota Road Research Facility (MnROAD) was conducted to determine the subsurface condition near transverse joints including the presence and/or extent of potential flaws.

Joint Degradation

Multiple MIRA scans were taken at various transverse joints in an initial screening. Analysis of the SAFT B-scans at one joint location showed some locations that indicated potential flaws. More detailed testing along the joint with scans taken in 3 inch step sizes showed the extent of the potential damage at the joint. Analysis of the SAFT B-scans taken in the right wheel path general area showed similar results to that shown in Figure 4. An example SAFT B-scan at a right wheel path is shown on the left in Figure 12. In this, and other locations around the right wheel path, the high intensity of reflection areas corresponded to dowel locations and the depth of the concrete-base interface as should be expected for undamaged concrete. Analysis of the remaining portion of the joint indicated a much different subsurface condition. Subsequent measurements at the center of the joint as well as moving toward the centerline of the joint indicated damage. Instead of strictly reflections at the dowels and concrete thickness, there was an uneven reflection at a shallower depth that should not be expected. This shallow and uneven reflection indicated deterioration of the concrete at the interface with the base.

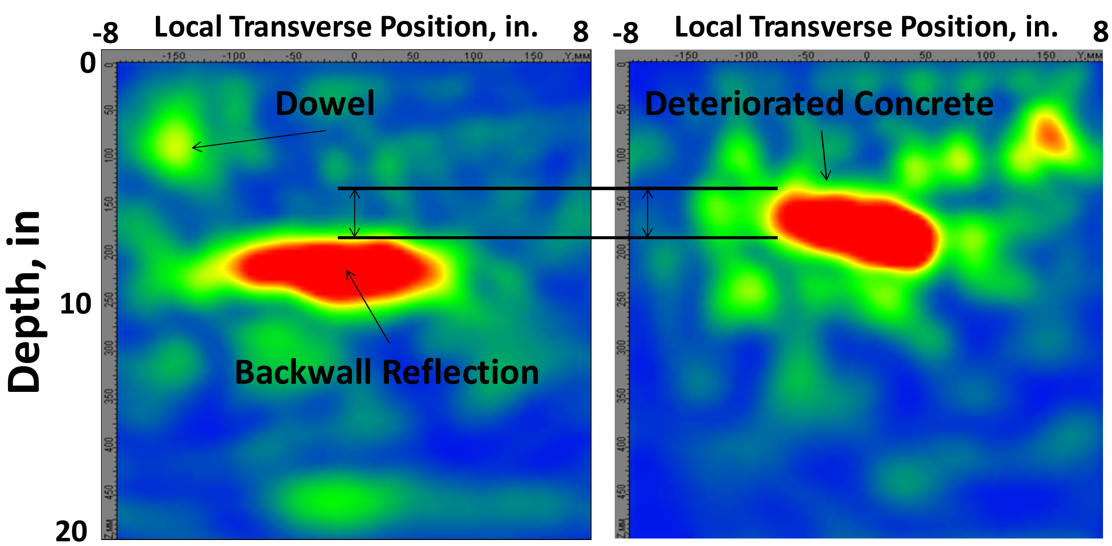

Figure 12. MIRA B-Scan locations in suspected sound (left SAFT B-scan) and deteriorating (right SAFT B-scan) conditions.

MnDOT personnel subsequently took a 12 ft by 3 ft full-depth concrete sample from along the transverse joint to verify the MIRA SAFT B-scan diagnosis. As shown in Figure 13, the sample was flipped so that the interface between the concrete and base is shown at the top. It can be observed that the underside of the concrete near the right wheel path is in relatively good condition as was diagnosed by MIRA. The underside of the concrete near the base in the samples at the middle of the joint and at the centerline show significant deterioration.

This verified the nondestructive diagnosis of deterioration using SAFT B-scans prior to the forensic verification.

Figure 13. Forensic sample sections used to verify the concrete condition on the underside at various locations near the transverse joint.

CONCLUSIONS

The testing presented in this study showed that although chaining with experienced personnel can identify the general qualitative information, MIRA testing and analysis is an attractive alternative to improve diagnostic capabilities. Using analysis of SAFT B-scan real-time signals, ultrasonic tomography was able to identify the presence of debonding, pinpoint details with regards precise location (boundaries) of the debonding, reduce subjectivity of the diagnostics, and archive a quantitative record of the scan locations and results to allow for further analysis. In addition, ultrasonic tomography testing was conducted to diagnose the subsurface condition at various transverse joints. Analysis of SAFT B-scans and subsequent forensic analysis showed MIRA to be capable of identifying subsurface distress prior to manifestation at the surface. MIRA was also able to diagnose the location and severity of the concrete subsurface deterioration. While MIRA is an attractive tool for joint condition and partial depth repair bond condition evaluation, some steps can be taken to make the measurement process and evaluation more user-friendly. A provisional specification for MIRA testing of transverse joints and partial depth repair quality control would be beneficial in making the measurement process and signal interpretation more productive for routine diagnostics.

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REFERENCES

Gucunski N., Romero F., Kruschwitz S., Feldmann R., Abu-Hawash A., Dunn M., “Multiple Complementary Nondestructive Evaluation Technologies for Condition Assessment of Concrete Bridge Decks.” Journal Transportation Research Record: Journal of the Transportation Research Board of the National Academies. Volume 2201. Pages 34-44. 2010. Online Date: Wednesday, December 01, 2010.

Gucunski, N., Rascoe, C., Parrillo, R., Roberts, R. L., “Complementary Condition Assessment of Bridge Decks by High-Frequency Ground-Penetrating Radar and Impact Echo.” Rutgers University. Paper #09-1282. Transportation Research Board 88th Annual Meeting, 2009.

Abdallah I. N., Williams R., Nazarian S., “Application of Data Fusion Using Fuzzy Logic Method to Nondestructive Evaluation of Pavements.” Transportation Research Board 88th Annual Meeting. Report Number: 09-3078. 2009. 15 pages.

Li, J., Zollinger, D.G., Lytton, R.L., “Detection of Delamination in Concrete Pavements Using Ground-Coupled Ground-Penetrating Radar Technique.” Transportation Research Record: Journal of the Transportation Research Board, Volume 2087 / 2008, pp. 68-77, 2008

Maierhofer C., “Nondestructive Evaluation of Concrete Infrastructure with Ground Penetrating Radar.” Federal Institute for Materials Research and Testing (BAM) Berlin, Germany. Journal of Materials in Civil Engineering. ASCE. Volume 15, Issue 3, Issue Date: May/June 2003, pp. 287-297.

Chong K. P., Carino N.J., and Washer G., “Health monitoring of civil infrastructures.” National Science Foundation, National Institute of Standards and Technology, and the Federal Highway Admisistration. Institute of Physics Publishing. Smart Materials and Structures PII: S0964-1726(03)61742-8, Date: 2003, pages 483–493

Rao, S. Hoegh, K. Yu, H.T. Khazanovich, L. “Dowel Alignment Constructability Evaluation In Portland Cement Concrete Pavements,”. accepted for publication in Transportation Research Record: Journal of the Transportation Research Board, Washington D.C. 2009.

Hoegh, K., T. Yu, and L. Khazanovich, "MIT SCAN Application in North America-Five Years After." Proceeding of the Ninth International Conference on Concrete Pavements, 450–462, San Francisco, CA, USA, 2008.

Hossain, S., Elfino, M.K., "Field Demonstration of Magnetic Tomography Technology for Determination of Dowel Bar Position in Concrete Pavement." VTRC 06-R40, Virginia Transportation Research Council, June 2006.

Khazanovich, L., H.T. Yu, and R. Stubstad, "Nondestructive Dowel Bar Detection in Existing Rigid Concrete Pavement Slabs." Sacramento, CA: California Department of Transportation, 2003

Washer, G., Fenwick R., Bolleni N., and Harper J. "Effects of Environmental Variables on Infrared Imaging of Subsurface Features of Concrete Bridges." Journal Transportation Research Record: Journal of the Transportation Research Board. Publisher: Transportation Research Board of the National Academies. Volume 2108. 2009. Pages 107-114.

Clark, M. R., D. M. McCann, and M. C. Forde. Application of Infrared Thermography to the Non-Destructive Testing of Concrete and Masonry Bridges. DT and E International, Vol. 36, No 4, 2003, pp. 265–275.

Maser, K. R., and W. M. K. Roddis. Principles of Thermography and Radar for Bridge Deck Assessment. Journal of Transportation Engineering, Vol. 116, No. 5, 1990, pp. 583–601.

Gibson, A. and Popovics, J.S. "Lamb Wave Basis for Impact-Echo Method Analysis." Journal of Engineering Mechanics / Volume 131 / Issue 4, 2005.

Mayer, Klause et al. *Characterization of Reflector Types by Phase-Sensitive Ultrasonic Data Processing and Imaging. Journal of Nondestructive Evaluation* (2008). Springer Science. Pp. 35-45.

Nesvijski, E.G., "On the Problem of Application of the Conic and Exponential Wave Guiding Extensions for Ultrasonic Transducers for Materials Testing". Journal: NASTA Technical Bulletin, Philadelphia, PA, USA, 1997 (ISSN 1079-8498), Volume 3, pp. 49-56.

Khazanovich, L., R. Velasquez, and E. Nesvijski (2005). "Evaluation of Top-Down Cracks in Asphalt Pavements Using a Self-Calibrating Ultrasonic Technique" *Transportation Research Record: Journal of the Transportation Research Board*, No. 1940, pp. 63–68.

Langenberg, K.J. et al. *Inverse Scattering with Acoustic, Electromagnetic, and Elastic Waves as* Applied in Nondestructive Evaluation. Chapter 2 in Wavefield Inversion. Edited by Armand Wirgin (2001).

Marklein, R. et al. *Linear and Nonlinear Inversion Algorithms Applied in Nondestructive Evaluation. University of Kassel. Inverse Problems* (2002). Inst. of Physics Publishing.

Schubert, Frank and Köhler, Bernd. *Three-Dimensional Time Domain Modeling of Ultrasonic Wave Propagation*. Fraunhofer Institute for Nondestructive Testing, Dresden Germany. Journal of Computational Acoustics (2001). IMACS. pp. 1543-1560.

Hoegh K., Khazanovich L., Yu H.T. "Ultrasonic Tomography Technique for Evaluation of Concrete Pavements. Transportation Research Board 90th Annual Meeting. Report Number: 11-1644 Pre-print (Recommended for Publication). 2011.