Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 4(3):176-184

Radar Technique Application in Structural Analysis and Identification of Interlayer Bonding

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Abstract: The paper discusses opportunities for evaluation of the asphalt pavement interlayer bonding quality with the use of GPR (Ground Penetrating Radar) techniques. The laboratory measurements were performed using a single 2 GHz, air-coupled, impulse antenna (in the simple reflection configuration) for the collection of synthetic samples representing idealized models of horizontal delamination. The measurements provided estimations of the antenna resolution in detecting cracks under dry and wet conditions. This analysis of the "ouble reflection" being a distinguishing feature of delamination allowed to formulate an important conclusion as to the critical limitations of the measuring system and as to the adequate methods of signal processing and interpretation. The field investigations consisted of GPR measurements (using the same antenna) along selected road sections and collecting drilling cores at locations associated with strong double reflections. The preliminary inspection of the drilling cores provided some insight as to the what laminas causing the double reflections are in real world road surfaces. They are not necessarily thin horizontal cracks but frequently they are a few centimeters thick deterioration zones associated with weathering (mineral changes and erosion of the aggregates, stripping the asphalt matrix off).

Key words: *Ground Penetrating Radar; Interlayer bonding; Pavement; Signal processing.*

Introduction

A proper bonding between all layers of the road surface is one of the key parameters taken into consideration during the construction stage. A 'proper' bonding means, in this case, a bonding which guarantees that tensile strains caused by road wheels of vehicles are transferred to the lower located layers. It is, therefore, desired that the layers positioned directly on top of each other be coherent and form a uniform complex (structure). The condition of the interlayer bonding considerably impacts the functional characteristics of the road surface, but is primarily defining its durability, especially if the bonding between two layers is subject to outside factors, such as water. Hence, a proper bonding has a twofold function: it increases durability of the road surface structure as a whole, and prevents water from penetrating the space between the individual layers.

Due to the critical significance of the interlayer bonding for the quality of newly constructed and modernized roads, diagnostic tests of road structures are becoming ever more frequent and are aimed at identifying the quality of the said bonding. Until now, laboratory tests such as the Leutner method or the Shear Box Test, have been the most popular ones. They are based on testing surface samples collected from drill cores. As it is usually the case with laboratory testing, the quantity of the samples collected and the point-specific character of information generated during such tests are among the most significant drawbacks of the method. Therefore, when evaluating various surface examination methods ever more emphasis is placed on NDT (Non-Destructive Testing) methods such as the Impulse Hammer Test [1] or the FWD (Falling Weight Deflectometer) test [2, 3], allowing to supplement, or in some cases replace laboratory methods.

The GPR (Ground Penetrating Radar) is one of the non-destructive testing methods that become standard in pavement evaluation [4-6]. Upon becoming acquainted with the basic applications of this method one gets an impression that the method is relatively easy to use and effective. It is so when the suitability of the method is assessed in relation to simple measurements, such as evaluation of the continuity (homogeneity) of road surface structural layers. However the technique carries also significant unused potential and creates great opportunities for road surface assessment purposes.

This article presents preliminary results of research aimed at evaluating the radar method's suitability for identifying interlayer bonding, and at applying the method along with other diagnostic techniques, such as the FWD. A number of laboratory tests have been carried out at the initial stage of the process, with the use of idealized laboratory samples, in order to determine the frequency of the antenna used to identify delamination cracks, as well as to identify the limitations related to the use of the test method in question [7]. Field tests have also been carried out along selected road sections, e.g. along the experimental section on which various bonding between individual asphalt layers have been simulated.

GPR Measurement System

The measurement systems as used in geo-radar based methods are made up of an impulse generator that forms impulses of prescribed frequency and power, an antenna that emits the electromagnetic impulse towards the surveyed object and a recording module that processes and records the reflected signals. The electromagnetic impulses produced are short, focused wave packages in the meaning that the head package (head signal) is characterized by a high

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Note: Submitted May 21, 2010; Revised September 23, 2010; Accepted September 23, 2010.

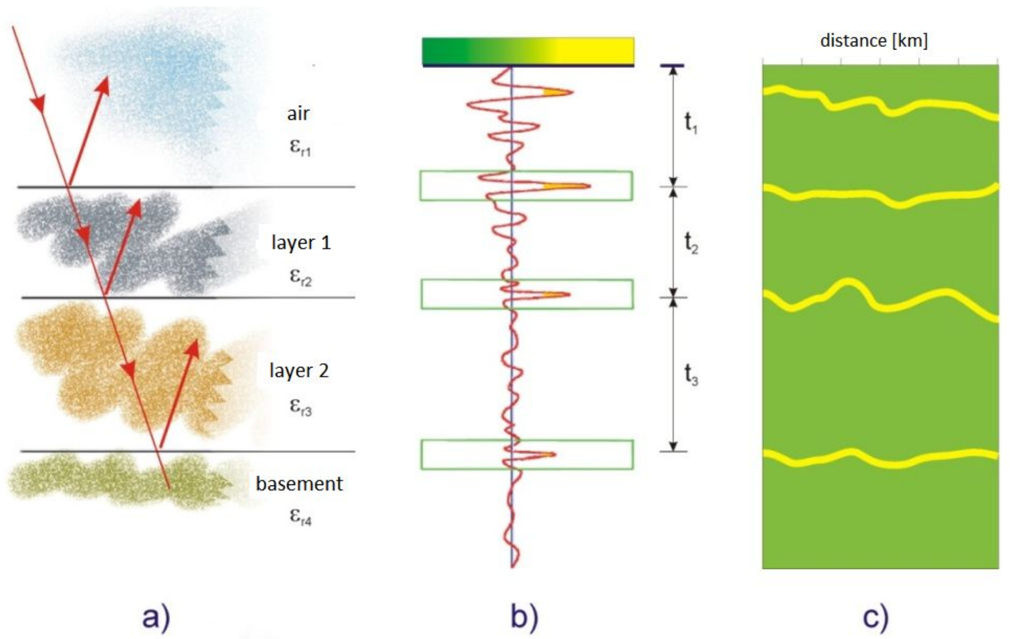


Fig. 1. GPR System Signal Recording Principle: a) Simplified Image Depicting Passage of the Electromagnetic Impulse through Air and Subsequent Layers 1, 2 etc., Combined with the Generation of Signals Reflected by Interlayer Borders; b) Reflected Signal Received; c) Simplified Radar Measurement Echogram.

amplitude and is composed of a low number of oscillations (e.g. three semi-periods), while the long persisting following fluctuations called the tail of the signal (created as a result of internal reverberations in the antenna) are characterized by a relatively low amplitude. Thanks to such a simple shape and large amplitude of the head package the copy of the impulse can be easy identified what means also that the moment at which it arrives at the receiving antenna may be precisely positioned in time.

The electromagnetic impulses emitted towards the surveyed structure penetrate the subsequent layers of materials characterized by varying dielectric properties, and are subject to partial reflection at the borders of the individual layers. This allows estimating the time of return and the amplitude of the signal reflected at the borderline between materials of various dielectric properties (Fig. 1). Those properties are, from the radar technique's point of view, crucial and clearly determine the form of the image obtained.

The GPR used for road surface evaluation may be divided into two groups: ground-coupled and air-coupled (horn) antennas. Due to the effectiveness-related requirements, road surfaces are usually assessed with the use of horn-type antennas, with the central frequency of approximately 1 GHz and the mean penetration depth of 60 cm. Antennas of this type are positioned approximately 45 cm above the surveyed surface and are installed on a test vehicle, which allows the measurements to be conducted without stopping the traffic.

For more detailed road surface testing horn type antennas with the central frequency of 2 GHz are used. This type of antenna has the advantage of a higher vertical frequency, allowing identifying very thin surface layers whose depth varies from 2.5 to 3 cm [8]. Just as it is the case with other antennas, they are positioned approx. 45 cm above the surveyed road surface on a test vehicle, often coupled with another horn-type antenna, e.g. with the frequency of 1 GHz, which improves the effectiveness of radar measurements carried out during a single passage.

During the laboratory and field tests a GPR system by GSSI, model SIR-20 has been used, equipped with a horn-type antenna with the central frequency of 2 GHz.

Laboratory Tests Focused on Detecting Delamination Cracks

The laboratory tests aimed at determining what type of the reflected signal is characteristic for the presence of a vast and widespread (spread horizontally) delamination crack, as well as at determining the chances of its detection under field conditions.

The primary objective of the laboratory tests was to determine the type of reflected signals created while examining the simplest of multi-layer structures. The aim was also to define what type of signal may be expected as a proof of the presence of a vast and widespread delamination crack. Having conducted preliminary tests it turned out that the laboratory layer system model (including a system with a delamination crack) should be of a considerable size (here about 2 meters in both horizontal directions; 2 GHz antenna), for when the edges of such a system are within range of the antenna's radiation cone, considerable diffraction effects are observed that hinder interpretation of those elements of the signal that represent a multilayer structure with delamination, and which elements of the signal represent the dissipation of the wave created on the edges of the test sample. In consideration of the mentioned technical difficulties it turned out that large format acrylic panels constitute the most suitable and easiest to use material to simulate various layers and cracks. It turns out that a single, thin dielectric

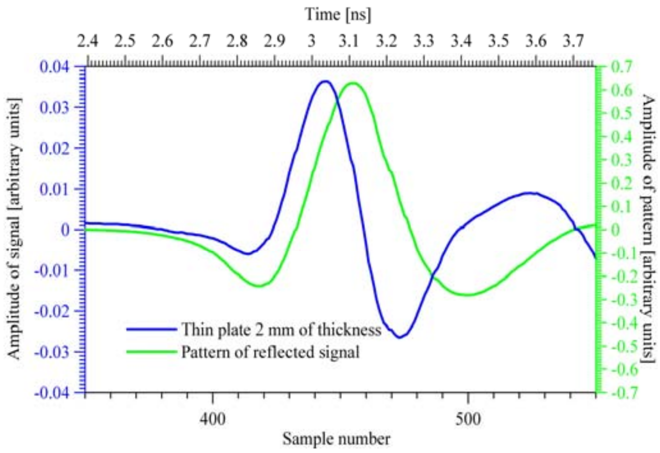


Fig. 2. Comparison of a Geo-radar Signal Reflected from a Thin (1.9 mm) Acrylic Panel ("Double Reflection"; Blue Curve) and a Signal Reflected from Sheet Metal ("Single Reflection"; Green Curve).

panel, e.g. an acrylic one, is a suitable and idealized laboratory model of a delamination crack [9]. By using it, one avoid interference of the head signal generated by the crack with the strong head signal of the surface reflection should the crack be located close to the surface of the panel stack, and on the other hand one avoid construction of a very thick pile (several tenths of a centimeter of thickness) of panels, if the crack was to be located deep inside the pile, in order to avoid interference of three head packages belonging to the three signals (reflected from upper surface of the pile, reflected from its bottom and the one generated by the crack in the middle of the pile).

Tests carried out with the use of thin acrylic panes allowed to determine the shape of the signal that heralds the presence of a vast and widespread delamination crack. Such a signal (Fig. 2, blue curve) differs considerably from a ***single reflection***, i.e. from a signal typical of a regular property contrast between two mediums contacting each other horizontally (Fig. 2, green curve). As long as the latter (single reflection) is similar to the $w(t)$ master signal registered for sheet metal reflection (with one leading extreme in the head package area), the reflection created on a thin panel or a crack has a shape similar to that of the signal's $dw(t)/dt$ derivative and has two adjacent leading extremes of opposite signs. Therefore, ***double reflections*** should be sought during field tests, as they are the ones that should depict a delamination crack. It turned out that the task was rather difficult in actual field tests, as the reflected signals are very weak and are effectively masked by the main peak. Even with the promising attempts to remove the masking peak, it is still difficult, at times, to distinguish between single and double reflections.

The reasons for which the reflected signal created when the wave passes a very thin crevice has a shape similar to the derivative of the input signal may be examined based on a simple model. Let the idealized crevice has the shape of a flat, horizontal layer filled with a medium whose electrical permeability equals ε' and whose magnetic permeability equals μ'. The medium above and under the crevice is characterized by the same parameters equaling ε and μ respectively, and the wave is flat and arrives at the delamination crack perpendicularly. The reflection (r) and transmission (t) amplitude coefficients (related to the change in electrical field oscillation amplitude) when the wave enters the crevice have the following values [10]:

$$r = \frac{p-1}{p+1}, \quad t = \frac{2}{p+1}; \qquad p = \sqrt{\frac{\mu\varepsilon'}{\mu'\varepsilon}}, \tag{1}$$

The aforementioned coefficients fulfill the following identity, expressing the energy conservation law:

$$pt^2 + r^2 = 1 \tag{2}$$

When the wave leaves the crevice, the amplitude reflection coefficient has the opposite value $r' = -r$, and the transmission coefficient value varies $t' = p \cdot t$. The signal generated by the crevice $f_R(t)$ by the wave $f_I(t)$ is made up of the wave reflected of the outer surface $r \cdot f_R(t)$ (referred to as zero outside reflection) and a series of waves with multiple internal reflections between the crevice's borderline surfaces:

$$f_R(t) = r \cdot f_I(t - t_0) - t \cdot pt \sum_{i=1}^{\infty} r^{2i-1} f_I(t - t_0 - 2\frac{d}{v'} \cdot i) \tag{3}$$

Wave i-th of the series is created as a result of the primary wave entering the crevice, $2i$-1 of internal reflections and the exit of the wave outside the crevice. All that modifies the original f_I signal by the $t \cdot pt \cdot r^{2i-1}$ factor, which signal is also delayed in time by $2d \cdot i/v'$ compared to the zero outside reflection; $v' = c/(\mu' \cdot \varepsilon')^{1/2}$ is the velocity of the wave in the medium filling the crevice. Multiple reflected waves are characterized by an important property determining that they are all of values opposite to the zero outside reflection, and their total amplitude (geometric series) has the value, based on Eq. (6), equal to that of the zero reflection:

$$t \cdot pt \sum_{i=1}^{\infty} r^{2i-1} = r \tag{4}$$

The mean delay τ of the internal reflection series waves may be worked out with the use of amplitudes as weights in averaging:

$$\tau = \frac{[\sum_{i=1}^{\infty} r(r^2)^{i-1} \frac{2d}{v'} \cdot i]}{\sum_{i=1}^{\infty} r(r^2)^{i-1}} = \frac{2d}{v'} \cdot \frac{\sum_{i=1}^{\infty} i \cdot (r^2)^{i-1}}{\sum_{i=1}^{\infty} (r^2)^{i-1}} = \frac{2d}{v'} \cdot \frac{1/(1-r^2)^2}{1/(1-r^2)} = \frac{2d/v'}{1-r^2} \tag{5}$$

As only several or about a dozen of the first terms of the series of internal reflections are crucial from the amplitude point of view, and the $2d \cdot i/v'$ time delays of those first waves of the series are then insignificant compared to the characteristic period T_c of the wave, the waves interfere constructively resulting in a signal whose shape and amplitude is similar to that of the zero outside reflection, but delayed by τ and of opposite value than the zero reflection:

$$f_R(t) \approx r \cdot f_I(t - t_0) - r f_I(t - t_0 - \tau) \approx r \cdot \tau \cdot f_I'(t - t_0 - \tau/2) = 2\frac{d}{v'} \cdot \frac{r}{1-r^2} \cdot f_I'(t - t_0 - \tau/2) \tag{6}$$

Therefore, the interference of the two components (zero reflection and the sum of multiple reflections) is considerably destructive, as the effective delay τ is also insignificant compare to the period T_c. The resultant signal may be therefore effectively estimated with the use of the derivative after the time of the applied signal. In some situations the reflection coefficient is considerably lower than one. Then, the denominator in the amplitude factor $r/(1-r^2) \approx r$ (when $r << 1$) may be disregarded, but when the maximum amplitude of the resultant signal is to be estimated, the maximum value of the f'_I function may be worked out by multiplying the central frequency of the applied signal $\omega_c = 2\pi/T_c$ and its maximum value $f_I|_{max}$, with $\lambda_c = v' \cdot T_c$:

$$f_R|_{\max} = 2\frac{d}{v'} \cdot \frac{r}{1-r^2} \cdot f'_I|_{\max} \approx 2\frac{d}{v'} \cdot r \cdot \omega_c f_I|_{\max} = 4\pi\frac{d}{\lambda'_c} r \cdot f_I|_{\max} \quad (7)$$

The formula allows estimating the effective amplitude of the signal generated by a thin layer. In a typical field scenario the wave approaching the crevice $f_I(t)$ is weaker than the master signal $w(t)$, and the reflected signal $f_R(t)$ is also weakened by passing indirect horizons, mainly by passing, twice, the outside surface of the road. Therefore, the additional amplitude weakening factor $\gamma \approx t_S \cdot p_S \cdot t_S = 1 - r_S^2$ has the value of approximately 80%.

$$g_R^{Double}|_{\max} \approx \gamma \cdot 4\pi\frac{d}{\lambda'_c}\frac{r}{1-r^2} \cdot w_I|_{\max} \underset{r<<1}{\approx} \gamma \cdot 4\pi\frac{d}{\lambda'_c} r \cdot w_I|_{\max} \approx g_N \quad (8)$$

The $w_I|_{max}$ symbol means the maximum amplitude of the master signal obtained as a reflection from metal sheet (with a similar return lead time), while g_R^{Double} is the registered amplitude of the double reflection. By comparing this amplitude to the noise level g_N, or to the level of other signals distorting the echogram (masking background amplitude), one may receive the layer detectability criterion. Similarly, the registered single reflection amplitude g_R^{Single} generated by the interlayer borderline (without delamination) has, in this model, the following form:

$$g_R^{Single}|_{\max} = \gamma \cdot r \cdot w_I|_{\max} \approx g_N, \quad (9)$$

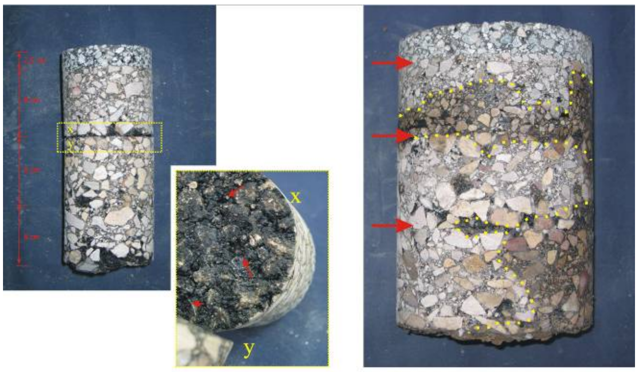
and its value has to be compared (as previously) to the level of masking distortions g_N in order to come up with the relevant single peak detectability criterion. High frequency electromagnetic noise has, under field conditions, a varying amplitude of $g_N / w_I|_{max} \approx 10^{-2},..., 10^{-1}$. Such noise is incoherent in time and may be effectively reduced by means of stacking, although typical GRP equipment offers no proper stacking opportunities, despite the fact such a means of registration fits potentially within its effectiveness limits. In the case of masking background, i.e. the residual signal of the "***background removal***" procedure, the level of interference $g_N / w_I|_{max}$ has the value of several per cent. Improvements introduced to the procedure allow to reduce it to approximately one per cent. The Eq. (8) determining the critical crevice detection criterion clearly indicates why a 2 GHz antenna is capable of detecting a 1 mm dry crevice, and a water-filled crevice even if its thickness measures several tenths of a millimeter. Laboratory tests have shown that a signal indicating the presence of a crevice whose width is expressed in single digits in millimeters is strong enough to be recorded and interpreted even under field conditions. Crevices with the width of several tenths of a millimeter also generate a recordable signal that is stronger than the background noise, but with the current state of the masking background removal technology it is difficult to distinguish between a double and a single reflection. Under field conditions a high, detection-enabling amplitude of double reflections is encountered frequently. It is so, inter alia, thanks to the presence of water in the delamination cracks, and thanks to the fact that such reflections are also generated not by thin, but by considerably thicker cracks, strongly porous zones of significantly degraded material, often soaked with water.

The single reflection is known under a working term of a positive reflection if its polarity is equal to that of the reflection formed during a reflection from a sheet of metal, i.e. it corresponds to contrast horizon between one material and a material with a lower velocity located underneath. A negative reflection accordingly corresponds to an opposite material contrast. If the single reflection $w(t)$ has one central peak (such a shape facilitates identification presence of the reflection, its type and assigning a return lead time thereto), the double reflection $dw(t)/dt$ in such a GPR system has two highest amplitude peaks. A single reflection is referred to as a positive one if the first peak of the leading extremes is positive (i.e. its sign is equal to that of the leading peak of the positive single reflection), and this type of reflection is relevant for the crevice-filling medium whose velocity is lower than that of the surroundings. In the case of road surfaces all the aforementioned conditions will be met in a situation in which there is a water-filled crack in asphalt. A double reflection is accordingly referred to as a negative one if the first peak of the amplitude-leading pair of extremes is negative, which corresponds to a crack filled with material whose velocity is higher than that of the surroundings, i.e. a dry, air-filled crack, or a crack filled with powdery, dry and porous material. As one can see, distinguishing between the types of reflections and identifying their signs is of fundamental diagnostic significance, and the relevant properties may be confronted with results of core drillings.

Field Measurements

The results presented in this paper are based on preliminary attempts to assess the condition of interlayer bonding, performed in real life conditions. Several examples have been selected to illustrate the potential and the limitations of the methodology adopted.

Test road sections have been selected based on general-character and scarce archive information. Radar measurements have been carried out at those sections, pinpointing those fragments of the pavement on which one could expect (based on documentation and/or results of geo-radar measurements) the existence of problems related to interlayer bonding. In order to verify the condition of the road structure drills have been made at specific locations (selected based on range finder readings, GPS, and measurement of distances to specific landmarks, as well as video recordings of the road). The cores have been then subjected to visual analysis.



a) b)

Fig. 3. a) Core La Collected in 2009 (Core Diameter 10 cm)– Visible Lack of Bonding between Upper and Lower Bonding Layers, and Lack of Asphalt Binder at the Bonding and Large Empty Spaces; b) Core 1b Collected in 2007 (Core Diameter 30 cm, Arrows Pointing to Connections between Individual Layers) – Archive Photo, Made 48 Hours after the Sample had Been Collected, Dampness Still to be Seen at the Connections.

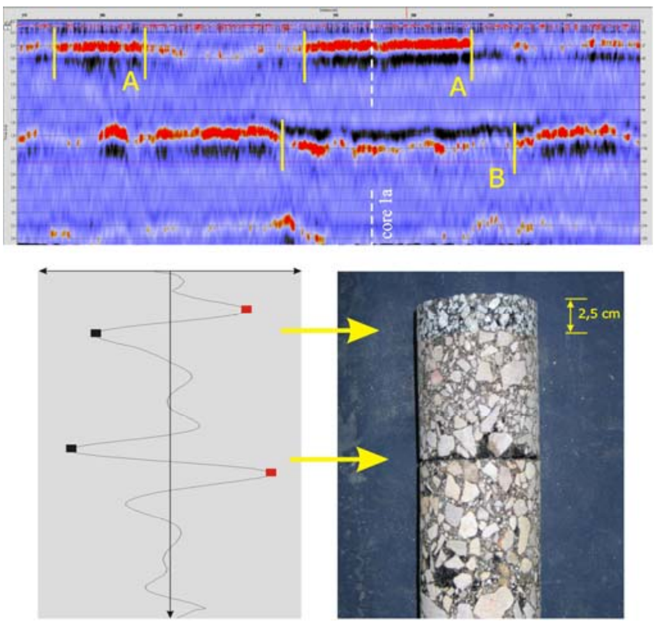


Fig. 4. Case 1. Fragment of an Echogram (Processed with the Use of the Standard "Background Removal" Procedure), Obtained During Measurements Conducted at a Section of Varying Characteristics and Accompanied by the Location of the Drill, Oscilloscope Image from the Radar Measurement at the Drill Location (Time Window 3.5ns) and a Photograph of Core La (Not to Scale). The Echogram Shows Changes in Amplitude and Sign of the Reflections corresponding to the Bonding between the Abrasive and Binding Layers (Sections with the Length of 7-10 m Marked as A) and Lack of Bonding between the Upper and Lower Binding Layers (Section Marked as B).

Case 1

Interesting results have been obtained on a relatively short (approximately 7 years) period of intense use (currently about 3,500 axles 100 kN/lane/day). The surface structure is made up of asphalt layers with the thickness of approximately 26 cm, positioned on a mechanically stabilized mineral compound layer. A sample of the surface from this section is presented in Fig. 3a (core1a), in which the lack of bonding between the upper and the lower bonding layer may be noticed (at the depth of approximately 10.5 cm). In the bonding zone one notices the lack of asphalt binder and large empty cavities between individual grains of the aggregate. Earlier drills performed at this section in 2007 indicated areas of dampness persisting at the bonding areas. Fig. 3b presents core 1b (collected in 2007 during rainfall, at the beginning of the winter season), in which dampness in the bonding zone persevered long after collection of the sample and its transfer to the laboratory.

The echogram recorded at this section is presented in Fig. 4. One can clearly see two depth ranges at which alterations of the recorded signal may be observed. The first one, approximately 0.4-0.6 ns from the surface, represents the border between the abrasive layer and the upper bonding layer. In this range one may notice appearing and disappearing pairs of positive-negative reflections (red-black, A), with the largest amplitudes recorded at two sections with the length of 7-10 m each. The echogram suggests delamination at the connection between the abrasive and the binding layers. Meanwhile, apart from the visually observed, increased amount of free spaces in the lower regions of the abrasive layer, the collected surface sample has failed to indicate more considerable damage. In the second range, 1.6-2.2 ns from the surface, a double reflection may be observed with its sign changing along the profile. The time position of this reflection corresponds to the border between the upper and the lower binding layers, which is confirmed by the core. The negative double reflection as seen in the oscilloscope image (black-red, B) from the sample collection location indicates that there is no bonding between the layers in the middle of the cross-section. Such a position of reflections also indicates that there is no water in the bonding zone. Opposite polarity of the signal at adjacent sections suggests, meanwhile, that there is water in the bonding zone. It may be the case that there is no bonding between both asphalt layers at those sections, but such a claim would have to be verified by collecting pavement samples. Nevertheless, data from the drill (core 1a) and archive data indicate that the problem of improper bonding between the bonding layers is typical for the entire section. The bonding between the layers is additionally subjected, at some locations, to water penetrating from the road lane divider. The echogram in question (Fig. 4) shows the reflection horizons positioned parallel to the outer surface of the asphalt. Therefore, the shape of reflection signals may be considerably distorted as a result of applying the standard "background removal" procedure, which makes the definition of the type of the reflection (single or double) and its sign (positive or negative) uncertain (see Case 4), and any assumptions must be verified by inspection of the core.

Case 2

On another section improper bonding between the binding layers was identified at the location at which the anti-crack netting is built in. The section was resurfaced in 2008. An asphalt overlay with the thickness of approximately 12 cm was placed on the existing

Fig. 5. Cores (diameter 10 cm) Collected in 2009. a) Core 2a Collected at the Right-hand-side Wheel Track, in Which the Lack of Bonding between Upper and Lower Bonding Layers is Visible; b) Core 2b Collected in the Center of the Hard Shoulder – the Bonding of Layers has been Visually Assessed as Good.

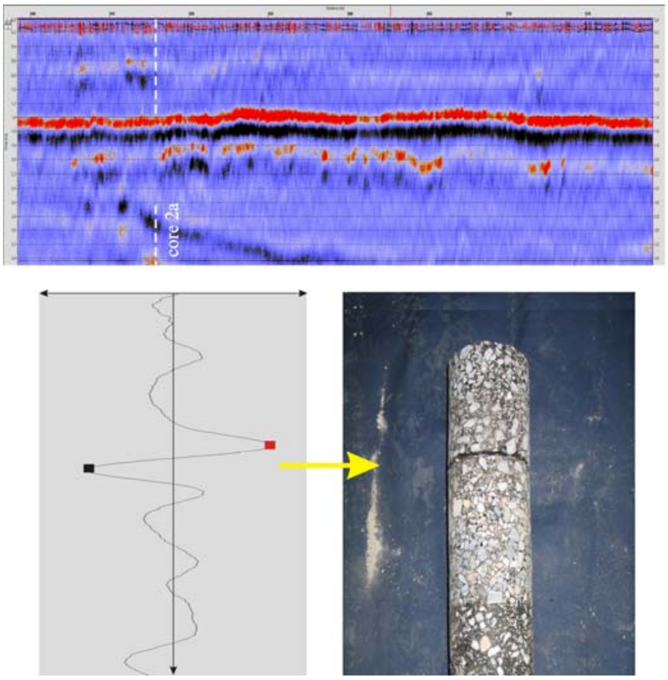


Fig. 6. Case 2. Fragment of an Echogram (Processed with the Use of the Standard "Background Removal" Procedure), Obtained During Measurements Conducted at a Section of Uniform Characteristics (Double Reflection Recorded at the Same Depth Under the Surface Throughout the Entire Section) and Accompanied by the Location of the Drill, Oscilloscope Image from the Radar Measurement at the Drill Location (Time Window 3.5ns) and a Photograph of Core 2a (Not to Scale). A Pair of Reflections Visible at the Entire Section, Corresponding to the Loss of Bonding between the Binding Layers at the Depth of the Built-in anti-crack Netting.

surface, with a fiberglass anti-crack netting built-in (at the depth of 9 cm) (core 2a, Fig. 5a). The use of netting without a special anti-slip layer has weakened the bonding of the layers and has resulted, due to heavy truck traffic (presently about 2700 axles 100 kN/lane/day), in the loss of bonding between them.

For comparison, a sample from the hard shoulder was collected at the same location (Fig. 5b, core 2b). Based on visual assessment it was determined that the bonding is good at the depth of the anti-crack netting.

The echogram registered at this section is presented in Fig. 6. A clear positive, double reflection is visible throughout the entire section, 1.2-1.8 ns from the surface, representing a lack of bonding between asphalt layers at the depth at which the anti-crack netting is built in. The type and sign of the reflection indicate the presence of water at the bonding. However, due to the contrast between wave velocity of glass and asphalt, one may suspect that such a shape of the recorded signals is caused by fiberglass netting, causing a local decrease in the velocity of the electromagnetic wave.

Similarly to Case 1, reflection horizons are parallel to the outer surface of asphalt. Therefore, application of the standard "background removal" procedure makes the definition of the type of the reflection (single or double) and its sign (positive or negative) uncertain (see Case 4), but the interpretation has been confirmed by with the help of the core.

Case 3

Sections with long and "eventful" history are most difficult to assess. The surface at such sections is often very much deformed and not uniform, which considerably hinders even the most rudimentary interpretation of data, not to mention such subtle measurements as an attempt to evaluate the condition of the bonding between the individual layers of asphalt.

The surface structure (Case 3) is not subject to considerable traffic loads (currently approximately 860 axles 100 kN/lane/day), and has been in use for over 20 years. The surface is made up of asphalt layers with the thickness of approx. 16-18 cm, placed on the layer of a cement concrete. Surface samples (Fig. 7, core 3a and Fig. 8, core 3b) have been collected at two different locations approximately 20 meters apart, and the drill locations have been chosen based on the echogram (Fig. 9), which indicated the lack of an interlayer bonding at those locations.

The sample marked 3a shows a cross-section of the road surface with a horizontal zone, positioned at the depth of 6 cm, whose properties differ considerably from those of the layers situated directly above and beneath. The thickness of this zone is approximately 2.5 cm, and its porous structure is similar to that of pumice. Upon breaking the layer, humid, clay-like residues of light-brown color were identified, filling the space between and surrounding the aggregate grains. The residues are most probably a product of degradation of lime aggregate grains subjected to water and low temperatures. One may assume that the atmospheric carbon dioxide contained in the asphalt-penetrating water has considerably

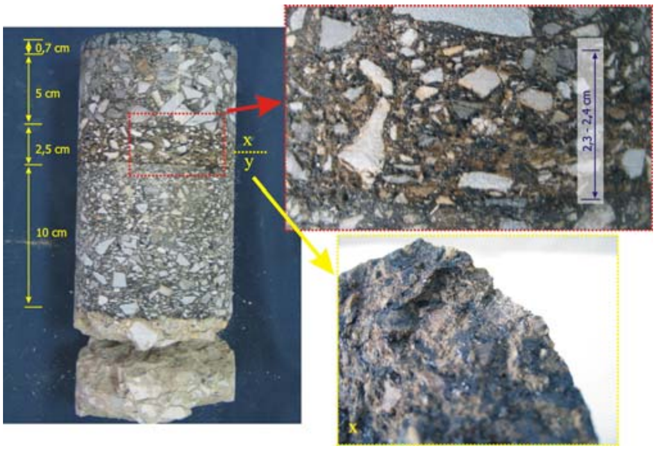


Fig. 7. Core 3a – a 2.5 cm Thick, Pumice-structure-layer at the Depth of Approx. 6 cm. The Cross-section of the Layer shows the Results of Aggregate Degradation and Insufficient Amount of Asphalt Binder.

Fig. 8. Core 3b – No Bonding in the Binding Layer, Fully Exposed Aggregate Grains at Connection Surfaces (Asphalt Binder).

facilitated erosion of the carbonate aggregates used for the construction of the road surface, and the light-brown discoloration suggests the participation of oxygen in the oxidation of minerals with a ferrous compounds content. In addition, insufficient amount of asphalt binder has been discovered (which has been washed out by water), which formed, in the broken sample, a cobweb instead of having the form of a uniform film surrounding the individual grains. No lack of bonding between the asphalt layers has been identified, and the core has been broken, in the zone with mineral abnormalities, under laboratory conditions, without the use of any tools, which proves the mechanical weakening of the zone in question.

The sample marked 3b shows a cross-section of the surface structure in which there is a crevice between the asphalt layers, at the depth of approximately 9 cm. In the delamination zone one may clearly notice the lack of asphalt binder and fully exposed aggregate grains, probably a result of water penetration. The condition of individual layers, their quality and structure raise no reservations upon visual inspection.

Radar data recorded at this section (Fig. 9) clearly pinpoints the location at which the structure of the surface has been modified. The first section from which core 3a was collected is characterized by a fairly stable signal. A positive double reflection is visible at this section at the depth of 0.8-1.4 ns from the surface. According to the adopted interpretation methodology, such a radar image should indicate a poor, humid bonding between the layers of asphalt. But the image of core 3a (Fig. 7) indicates that the bonding of all asphalt layers is at least good. The examined cross-section is characterized by an uncommon, structure-wise, zone with advanced material degradation of thickness about 2.5 cm, positioned at the depth of 6-8 cm. It is this zone that "generates" a signal whose characteristic is similar to that obtained at locations where complete delamination has taken place. One may assume that this highly porous zone was saturated with water when the measurements were made.

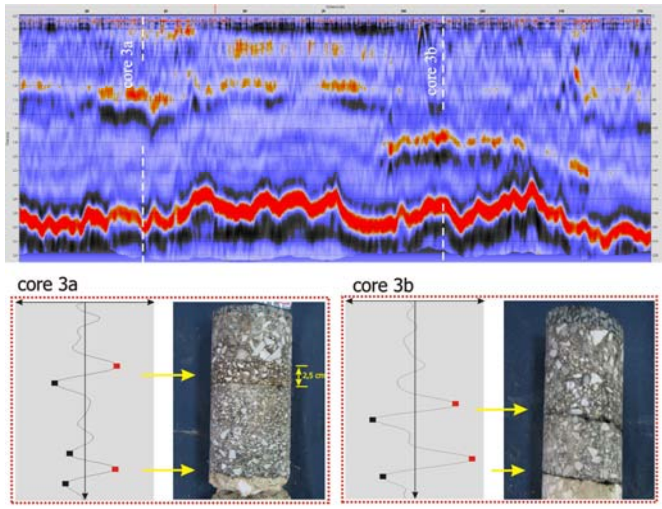


Fig. 9. Case 3. Fragment of an Echogram (processed with the use of the standard "background removal" procedure), Obtained During Measurements Conducted at a Section of Varying Characteristics (reflections are not parallel to the surface, at the entire length of the section) and Accompanied by the Location of Drills, Oscilloscope Image from the Radar Measurement at the Drill Locations (time window 3.5 ns) and a Photograph of Cores 3a and 3b (not to scale). Yellow Echogram Markers Indicate Changes in the Structure of the Pavement.

At the other section, just as in the case of the first one, a double positive reflection is visible recorded 1.7-2.1 ns below the surface. This reflection represents delamination at 2/3 of the lower binding layer thickness (Fig. 8, core 3b). The double positive reflection visible in the echogram (peak layout, downwards: positive-negative, colors: red-black) indicates that there is no bonding between the layers and that water fills the delamination zone at the distance of approximately 10 m of the road surface.

In Case 3 identification of the type and sign of strong double reflections poses no such serious doubts as in Cases 1 and 2, even after the echogram being processed with the use of the standard "background removal" procedure, as the layout of the horizons responsible for the generation of those reflections is not parallel, at long sections (comparable to the length of the entire cross-section) to the road surface (see Case 4).

Case 4

The last of the examples illustrates the application of the standard

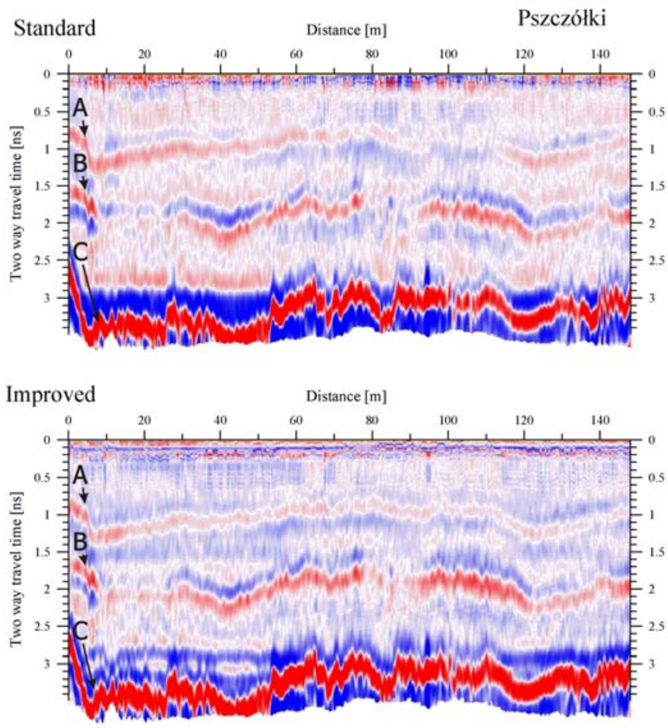


Fig. 10. Case 4. Fragment of an Echogram Obtained During Measurements Conducted at the Experimental Section. The Upper Image has been Obtained with the Use of the Standard (Upper Echogram) and the Lower of the Improved (Lower Echogram) Background Removal Procedure. Markings: A – Borderline between Abrasive and Binding Layers, B – Borderline between Binding Layer and Asphalt Understructure, C – Borderline between asphalt understructure and Loose Understructure.

and author-devised radar signal post-processing method. The data presented (Fig. 10) were obtained during measurements conducted at an experimental road section, on which various types of connections between the bonding and base layers have been used (horizon B). Varying interlayer bonding characteristics were obtained by changing the sprinkling volume, and lack of bonding was simulated by applying, between the layers, dust and clay paste. The total of 7 sections has been prepared with the length of 20 m each. A more detailed description of the test section may be found, inter alia, in the publication [11].

The upper echogram presents the results of the background removal procedure. The standard version of this procedure (deleting the averaged signal following a time-zero correction) is not sufficiently flexible in removing major background components and the residual signal, after the masking signal has been removed in an improper manner, remains the major factor distorting the recorded signals. It is possible, however, to enhance this method and improve legibility of the echogram, as presented in the lower echogram.

The structural cross-section obtained shows, aside from the border between the asphalt layer and understructure (strong single, positive reflection marked C), two clearly visible horizons in the asphalt layers package (marked A and B). Comparison of both echograms shows that the quality of the entire image has improved. The greatest improvement is observed in the part that is closest to the surface, i.e. at the depth of 0-1.5 ns. In this area the borderline between the abrasive layer and the binding layer is recorded, which is much clearer in the lower echogram, particularly at 90-110 m. In addition, the lower echogram clears any doubts concerning interpretation of the type of reflection from this borderline, especially between 10-45 m and 115-145 m – which is obviously a single, positive reflection at the entire section. In the case of the standard background removal procedure (Fig. 10, upper), this reflection could be easily interpreted as a double one, due to its shape being deformed by removal of the averaged signal. Such a deformation occurs, in particular, in situations in which the reflecting horizon is located, at a longer section, parallel to the outer (upper) surface of asphalt. Average signal becomes then similar to the local signal recorded at this section, which results in considerable shape distortion during the signal removal process [12]. Modification of the processing method consisting in defining the background in a manner that is independent from the average signal (Fig. 10, lower) has allowed doing away with the phenomenon in question. The quality of reflections corresponding to the borderline between the binding layer and the understructure, i.e. where various types of connections were simulated, has improved as well. At 25-125 m the type of reflection needs to be interpreted as a double negative one, which means a poor bonding between both layers. Such an interpretation corresponds to the arrangement of the sections on which the lack of interlayer bonding has been simulated. The upper echogram, in turn, shows certain sections at which the reflection corresponding to this borderline could be interpreted as a single negative one (sections 25-55 m and 125-145 m) or a single positive one (55-75 m), which would lead to an incorrect interpretation of the condition so the interlayer bonding.

Conclusions

The geo-radar technique offers good delamination detection opportunities, if the delamination in question is extensive and developed to a degree that open (empty or filled with foreign material: air, water, clay-like substance), horizontal (spreading horizontally) crevices are created with the thickness of several millimeters. As indicated by laboratory tests and proven by simple calculations, such thin, internal delamination results in the generation of a reflected signal in the shape of a double peak, i.e. considerably different than the simple single peak corresponding to a horizontal material contrast at the borderline of two layers of significant thickness. The double peak allows evaluating the sign of the wave velocity contrast between the lamina and the surrounding material.

There are cases involving road pavement in which the double reflection is caused by an crevice interval (empty or filled internal lamina) between the individual layers of asphalt or within a single layer. Core drill results indicate, however, that situations in which the double reflection results from serious material defects in the shape of a horizontal layer (with the thickness of as much as several centimeters) inside the pavement, usually created at the point of contact between the asphalt layer, are no less frequent. Abnormalities observed in such zones include increased porosity caused by asphalt erosion, and if lime aggregates are used, considerable mineral alterations take place that prove the participation of oxygen in the reaction and show signs of erosive degradation of the rock material, caused by water and most probably carbon dioxide. The type of such degradation indicates participation of chemical factors (water, air, carbon dioxide) enabled by the loss of air-tightness and penetration by water. High porosity of material related to the presence of large cavities after eroded asphalt binders and/or eroded aggregate seems to be one of the decisive factors determining the effectiveness of reflected signal generation in significantly degraded areas. Both in the case of thin laminas and slightly wider degradation zones the presence of water in the highly porous damage zone seems to be crucial for the generation of double peaks. Unlike dry zones, which are often characterized by a double negative peak, humid zones generate a double positive peak whose absolute amplitude is considerably higher, thus offering higher potential for defect detection. The presence of humid areas is common under field conditions.

The diagnostic effectiveness is most seriously hindered by the difficulties in removing the background masking the structural signal. Its insufficiently effective removal (the standard background removal procedure) leads, inter alia, to considerable difficulties in distinguishing between single and double peaks. Preliminary tests have indicated the need for further research on the causes behind such difficulties, in order to foster development of a more effective masking background removal concept.

Laboratory tests, aimed at determining the limitations of the measurement system in question, have indicated a number of shortcomings of the method used for evaluation of the condition of interlayer bonding. Due to the difficulties in determining the physical factor generating the double reflection based solely on the echogram, it seems that the GPR is not (will be not) necessarily considered an independent diagnostic technique providing a final assessment of the condition of interlayer bonding, especially in the case of new, undeveloped cracks which are not accompanied by the presence of cavities. The technique renders, however, exceptionally promising results in the case of wide cracks and in the case of zones with advanced mechanical and chemical damage, which occurs, as it seems, along the crack after a certain period of time.

In the authors' opinion it is worth highlighting that a considerable portion of the results related to locations chosen for field testing have been confirmed by core dills. The above applies in particular to sections with relatively new pavements, in which the layout of individual layers is well-ordered and not deformed. This proves that GPR will greatly complement other direct and (NDT) methods, such as, e.g. the FWD method as described in [3]. Due to good productiveness, GPR measurements may become a key factor in preliminary identification of the condition of the road surface, especially in the case of advanced zone degradation, as described above.

Acknowledgements

This article presents preliminary results of research conducted under a scientific and research program financed by the General Directorate of National Roads and Motorways. Authors wish to thank Piotr Jaskuła, Eng., PhD from the Gdańsk Technical University for support and participation in the first stage of the project. Separate thanks go to Professor Dariusz Sybilski, for his valuable comments and motivation for writing this article.

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