

Evaluation of Homogeneity of Thickness of New Asphalt Layers Using GPR

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Executive summary. The use of GPR (Ground Penetrating Radar) as an auxiliary tool in assessing the structural condition of the road pavement is now a common practice. Such equipment is employed by both private consulting companies and main road management laboratories. The field of application of GPR is constantly growing. Radar techniques are combined with sophisticated methods of data analysis, which facilitates the process of assessment of damage to the pavement structure, such as cracks, inhomogeneity of compaction or the condition of interlayer connections. The primary role of GPR operators is to determine the thickness of layers, including new ones.

This article discusses the main elements of the method of measuring the thickness of new asphalt layers. This method can support the acceptance testing phase. Particular attention is attached to the methods for the calibration of the wave travel velocity, including the role of reference drill holes, their precise positioning and determination of layer thickness. The article revolves around the dispersion of measurements and uncertainty of average and local results, as well as pointing to the key factors having an influence over accuracy, which is of importance in the consecutive phases of acceptance testing.

Keywords: measurement of layer thickness, GPR, acceptance tests, measurement accuracy.

1. Introduction

The accurate measurement of thickness of pavement structure layers basically occurs in the assessment of roads intended for renovation and during the phase of acceptance tests of new pavements. While the former case does not pose any special challenges and falls within the designer's responsibility, the latter is more demanding, since the results may entail financial penalties imposed on contractors.

In assessing the thickness of asphalt layers, the most common approach is to collect a core sample from the pavement, as provided by the road manager. The thickness measurement can be carried out in accordance with the PN-EN 12697-36 standard. In recent times, the Ground Penetrating Radar (GPR) has been increasingly used to support the inspection process carried out as part of acceptance tests. Although the use of GPR clearly improves the quality of assessment of layer thickness homogeneity, still the sole application of this technique does not necessarily guarantee a high quality of data. No less important is the choice of methodology that takes into account strict data synchronization and the correct algorithm for determining the velocity of electromagnetic waves (related to electric permittivity value). Obtaining thickness results of satisfying quality from the GPR measurement depends, first and foremost, on the correct determination of electrical permittivity of the examined layer. There are four basic methods for assessing permittivity: reflectometric (described in this article)



reference drill holes [1, 2], laboratory measurement of electrical permittivity [3, 4, 5] and the common mid-point method (CMP) [6, 7].

This article discusses the methodology of measurement and data processing relying on data from core samples collected in locations selected on the basis of the initial analysis of radar data. This method requires a careful approach to the phase of field measurements; at the same time, it does not require complicated calibration methods or very expensive laboratory equipment. The described method can be successfully used in tests of asphalt and concrete pavements supporting the acceptance testing phase required in technical specifications, standards and national regulations. As regards concrete pavements, the specific nature of placed material should be considered along with the associated phenomena, such as significant microwave absorption and dispersion.

2. Typical measuring equipment and profiling

GPR measurements of the thickness of asphalt layers or of the entire package of asphalt pavement layers are usually performed by means of profiling (continuous scanning) along a selected line. Profiling is generally carried out along the road axis using a mobile GPR system intended for extensive road surveys (Fig. 1). The scanning system allows the use of various types of antennas, yet, in practice, the air-coupled impulse antennas with the central frequency f about 2 GHz are most advantageous, as they allow high mobility of the scanner and offer a very clear and high-resolution picture of the structure of asphalt package. Ground antennas with a similar central frequency have superior sensitivity and horizontal resolution, and they offer interesting results in detecting defects [8] but are used only for local tests with closed traffic due to mobility constraints. In overview surveys, it is possible to perform the measurement at a speed of 50 km/h or higher, but this is definitely inadvisable for measurements that require high accuracy in thickness determination. In such a case, the recommended speed is between 10 and 20 km/h, and individual profiling is done in subsequent passes. With such an organization, it is possible to ensure synchronization of the measurement distance with reference objects or other measurements with an imprecision of no more than 1 meter, which permits, for example, correct calibration of the wave velocity by drilling.



Figure 1. Mobile scanning system.

If the aim of measurement is to obtain a representative image of the layer thickness, as in acceptance testing, the so-called mapping is performed in the form of several scans (profiles) along the road axis, parallel to and equidistant from each other (Fig. 2). In order for the result of mapping to be considered reliable, the distance between the profiles should not be greater than 2 meters, and the profiles themselves should run on the center lines of belts of no more than two meters wide and covering the entire width of the examined road. On the other hand, the distance between the profiles should not be less than 50 cm because the main antenna radiation cone covers the oval road surface with a diameter of about 1 meter and produces, as a result of measurement at a given point, an image of the averaged (in some sense) package structure beneath this area. Maintaining the distance between the profiles of significantly less than 1 meter is also difficult to control in the field without drawing profile lines on the surface.

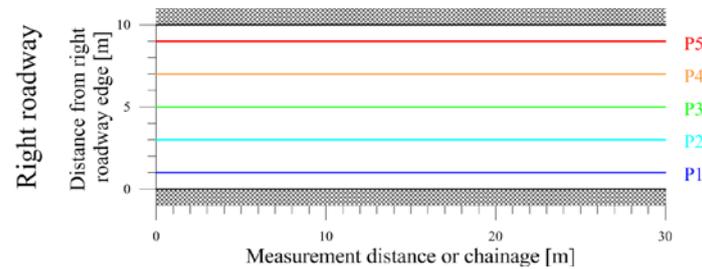


Figure 2. An example of the organization of a measurement profile system when mapping surface thickness.

3. Method of thickness measurement

The scanning process involves the transmission of a microwave pulse towards the pavement and recording the returning response signal. The scans are made at successive profile points at fixed intervals (e.g. every 10 cm). As a result of scanning and after the numerical processing of measurement data, an echogram is obtained (Fig. 3), i.e. a graphic representation of subsequent scans one next to another, where the amplitude of the return signal is shown as the shades of gray, the distance from the upper edge of the echogram corresponds to the time of return, and the numbers of subsequent scans reflect the measuring distance. The echogram is an image of the layered package structure, but it must be remembered that the vertical dimension is not a direct and simple equivalent of depth. This image is also partially diffractive, which is clearly seen in the areas of sudden changes in the layer structure and may cause shifts in the time of return in the case of significantly inclined boundaries. However, in the case of asphalt package layers (apart from area of local structural disturbances), the interlayer boundaries usually have very small inclinations in relation to each other within a one-meter distance scale, so that no adjustments (migration) are needed to compensate for the inclination.

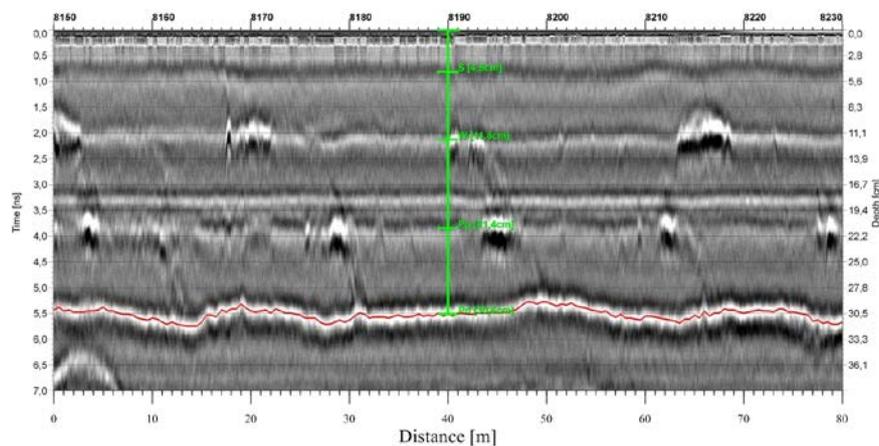


Figure 3. Example of half-velocity calibration $v_{1/2}$ of a package of asphalt layers. At value $v_{1/2} = 5.55$ cm/ns, a perfect match was achieved between the double travel time and the thicknesses marked in the drill hole.

Measurement of the thickness d of a layer package or a single layer involves the reading from the echogram the time t of wave travel through the package (or layer) and converting this time into thickness:

$$d = v_{1/2} \cdot t \quad (1)$$

Consequently, the main components of error in the determination of layer thickness come from the uncertainty Δt of double travel time t (DTT) and from the uncertainty $\Delta v_{1/2}$ of adopted half-velocity value $v_{1/2}$:

$$\Delta d \approx \sqrt{(\Delta v_{1/2} \cdot t)^2 + (v_{1/2} \cdot \Delta t)^2} \approx \Delta v_{1/2} \cdot t + v_{1/2} \cdot \Delta t \quad (2)$$

Although the scanning systems have a very good temporal resolution due to the signal sampling frequency, which potentially allows the relative positioning of reflecting boundaries with submillimeter accuracy, a limitation of the real temporal resolution is the width of the microwave pulse $\tau \approx T = 1/f$ and the ambiguity of interpretation of the actual shape of the return pulse. In the case of a simple single reflection [9] corresponding to the boundary where the material contrast occurs expressed in a stepped change of electrical permittivity, the basic uncertainty in determining the travel time comes from the difficulty of determining the time position of the interlayer reflection peak. Both manual and automatic procedures are employed to track this peak. The typical uncertainty of such a determination in a single scan is about one eighth of the wavelength (0.06 ns at $f = 1/T = 2$ GHz, i.e. about 3 mm of the determined layer thickness) or smaller. As long as the procedure does not involve a systematic shift of the determined time, the impact of this uncertainty is usually reduced when determining the average package thickness in a given road section.

Another vital and even much more important reason for uncertainty Δt is the deformations in the shape of the reflection [9]. The bottom reflection of the package is usually a strong single reflection (from the boundary with the contrast of electrical permittivity) and its peak is usually a good representation of the bottom package even if the signal is extended due to the small-scale fluctuation of bottom shape in centimeter and decimeter scales of horizontal variation. In contrast, the forms of interlayer reflections are often severely deformed. They take the form of double or mixed reflections [9, 10] and to identify them requires an experienced interpreter. Ambiguity in the interpretation of the shape of reflection may lead to a systematic, even quarter-wave error of $\Delta t \approx 0.125$ ns (2 GHz antenna), i.e. about 0.6 cm ($v_{1/2} \Delta t$) of layer thickness, and this error can increase (can be even doubled) if the mistake occurs both at the top and bottom of the layer. This component of error usually accounts for the uncertainty of measurement of thin, few-centimeter thick layers. In the case of very thin layers, limitation of the resolution of close horizons must be taken into account because the upper reflection begins to merge with bottom one when the thickness of a layer is less than half the wavelength in the material ($d < v_{1/2} \cdot T \approx 2.5$ cm at $f = 2$ GHz). In 2 GHz central frequency antennas, it is difficult to distinguish (convincingly) between the upper and lower boundaries of layers thinner than 3-4 cm. In some cases, when the layer presence is certain, the numerical signal modeling may prove helpful in determining its thickness [11, 12].

4. Main factors determining precise velocity calibration using reference drill holes

In the case of relatively thick packages (several decimeters), the effective thickness error Δd depends on the uncertainty $\Delta v_{1/2}$ of determining the wave half-velocity. In principle, this value (according to the definition) is a material property, expressed as half the velocity of travel of an electromagnetic wave of a specific frequency (the case without dispersion). Its value is determined primarily by the petrophysical type of rock factions, but also the content of the binder, the presence of voids, humidity and the spatial organization of aggregate grains have some influence [2, 13]. In the GPR method, however, this velocity is regarded as an effective property of material in a particular measurement (observed typical values range from 4.7 to 7.2 cm/ns). It is a formal factor for converting the time of double travel into layer thickness taking into account the various deficiencies of the measurement system and of the entire method of processing and interpretation. It is assumed that this is an average layer or package attribute, approximately constant, on a certain road section that is considered homogeneous. Its minor fluctuations are ignored. It is approached as an effective value (averaged vertically), also trying to cover the vertical changes of velocity most often resulting from the differences of compaction at different layer depths.

In the adopted method, drill holes are made in selected locations of the profile line, in places that can be precisely located on the echogram. The determined package (or layer) thickness d_r is divided by the time of wave double travel t_r recorded at this very location, thus obtaining a half-velocity estimate:

$$v_{1/2} = d_r / t_r \quad (3)$$

Hence, the uncertainty of such an estimate is expressed as:

$$\Delta v_{1/2} \approx \sqrt{\left(\frac{\Delta d_r}{t_r}\right)^2 + \left(d_r \cdot \frac{\Delta t_r}{t_r^2}\right)^2} \approx \frac{\Delta d_r}{t_r} + d_r \cdot \frac{\Delta t_r}{t_r^2} \approx v_{1/2} \cdot (\Delta d_r/d_r + \Delta t_r/t_r) \quad (4)$$

The calibration function of reference drill holes should be distinguished from their role in identifying a layered structure or in recognizing other package attributes (e.g. defects).

4.1. Mislocation of the reference drill hole

The key challenge in calibration is the accuracy of synchronization between the location of the drill hole and the corresponding formal GPR measurement distance on the echogram. The reason for that is the relatively high variability of package thickness that usually occurs along the measurement profile. In the measurement practice, to synchronize the distance on the echogram with profile locations, real and well-identifiable field reference features are used (chainage, lamp posts, geodetic markers, makeshift surface markers, intersections, etc.). After gaining more practice, it is possible to master the methods that help remove errors resulting from parallax observations, system latency, mistakes of individual observations, turns along the traveling route, etc. It is usually possible to achieve positioning accuracy better than 1 m.

One of well-proven and recommended practices is the drilling in locations carefully selected during the earlier analysis of echograms, i.e. in areas where the thickness variation visible on the echogram (in time domain $t_r(\mathbf{x})$) is negligible, and, thus, a two-meter mistake in the location (along the profile) does not cause any serious distortion of the reference thickness d_r .

There is an option of collecting a large number of drilled holes (e.g. all available results) and perform a statistical analysis of the determined velocities set while rejecting extremely distorted values or using other advanced methods discriminating incorrect measurements, i.e. the modeling of specific statistical properties of such a group.

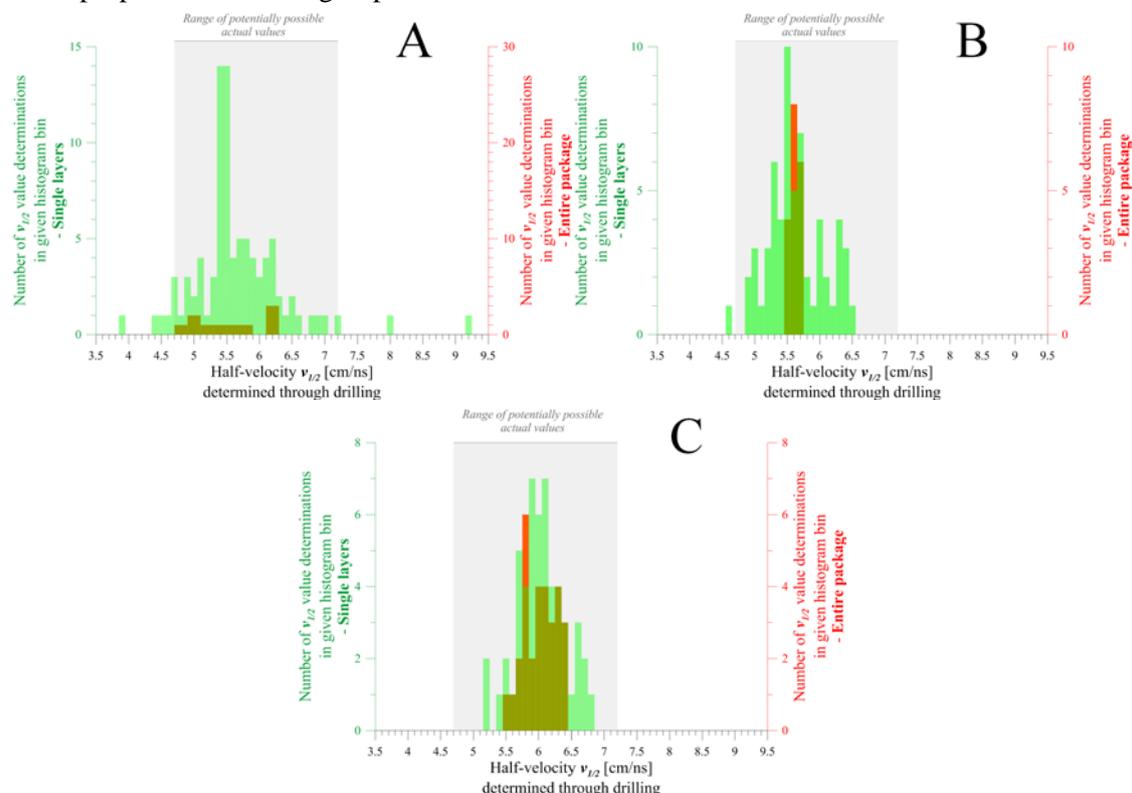


Figure 4. Examples of half-velocity histograms showing distribution of velocity estimated by means of A) data from a large group of previously made holes, i.e. without their precise location based on

echograms, B) a group of holes with a well-controlled positioning and C) a group of holes with a very poor positioning control after several attempts to verify the position, allowing its several-meter modifications.

In the practice of precise determination of thickness of an asphalt layer package, the optimal solution is to drill at least two holes on a 300-meter road section and one hole every 300 meters of its further length. The number of drill holes can be increased if some material differences are detected between the segments of a road section, or this number can be reduced if there are no material differences on a long section. To control the wave velocity effectively, the number of calibration holes should not be reduced to fewer than one per 1 km of the examined road.

4.2. Complications of the shape of the bottom surface of an asphalt layer package

As opposed to the interlayer boundaries, the bottom surface of an asphalt layer package usually reveals significant deformations in the form of undulations in centimeter and decimeter horizontal scales. This shape may be attributed to the unevenness of the previously laid subbase or may result from the interaction of the mineral asphalt mixture with underlying aggregate during incorporation. Such deformations of the boundary surface with scales comparable or slightly smaller than the wavelength in the medium are seen by the electromagnetic wave as a transition zone. When such a zone is encountered, the bottom reflection is extended [10].

Some examples of difficulties in measuring a layer package can be serious deformations and chipping of the bottom, the masking of the bottom by adhering subbase material or the penetration of the bottom of an asphalt package by subbase aggregate grains (Fig. 5). The uncertainty of such determination of package thickness in a single core sample may exceed 0.5 cm, which means that the final examination result is encumbered with significant uncertainty. In addition, in this situation, the uncertainty of a single core sample measurement may not reflect the actual thickness variations in the several-decimeter vicinity around calibration holes. One of the methods to control uncertainty and reduce its impact is to make several calibration drill holes and perform a statistical analysis of the set of determined half-velocities.



Figure 5. Examples of a complicated shape of the bottom surface of an asphalt layer package leading to significant uncertainty in determining package thickness on a core sample: A) significant losses and deformations due to insufficient bottom compaction, B) a well-defined flat surface partially masked by subbase aggregate grains from underneath, C) large aggregate grains (clearly larger than grains embedded in the package) penetrating the package bottom (clearly immersed in the asphalt mix).

4.3. Interlayer delamination

Several-millimeter errors in the determination of package thickness are usually attributable to interlayer delamination. In such cases, it is advisable to measure the thickness of layers after prior matching of collected core parts. It is much easier to perform it in a laboratory than in the field.

4.4. A challenging identification of thin layers

As shown by formula (4), there is a specific challenge in the calibration of velocities by means of drilling in the case of thin packages or single layers (Fig. 4B). The unavoidable uncertainties of reference measurements d_r and t_r translate into the very high uncertainty of velocity determination. For this reason, the method of velocity calibrating by means of drill holes is used primarily in relation to the whole package and without separating it into layers (velocity differentiation between layers).

Separation into layers is only used for beyond-average velocity differences between layers that can manifest themselves by strong reflections at the interlayer boundary.

5. Other methods of velocity calibration

Among the alternative methods of wave velocity determination there is the analysis of pavement reflectivity [14]; it is also used for effective identification of the material changes in the structure. It is an advanced technique that requires a lot of experience in the necessary measurement calibration procedures and data correction and processing due to the high instability of impulse measuring systems. The simplest and the most precise option in this technique is the analysis of pavement reflectivity which returns the measured wave velocity in the top pavement layer.

A common trend observed in the newly placed packages of asphalt layers is the use of an identical or very similar (when it comes to dielectric properties) set of materials, which can be recognized on the echogram as absent or extremely low amplitudes of reflections on interlayer horizons. In such a situation, the velocity determined in the top layer of the package tends to be regarded as typical also for the whole package. Thus, velocity stratification is somehow neglected, although it occurs, for example, when the lowest package layer is improperly compacted. However, such an approach seems to be very effective in practice if the calibration and adjustment procedures are carefully performed. Reflectometric determinations clearly refer to the calibration relying on drill holes (Fig. 6B), while in the case of thin packages or ones without exact positioning control, they can even be seen as superior to drilling when it comes to dispersion (Fig. 6A and 6C).

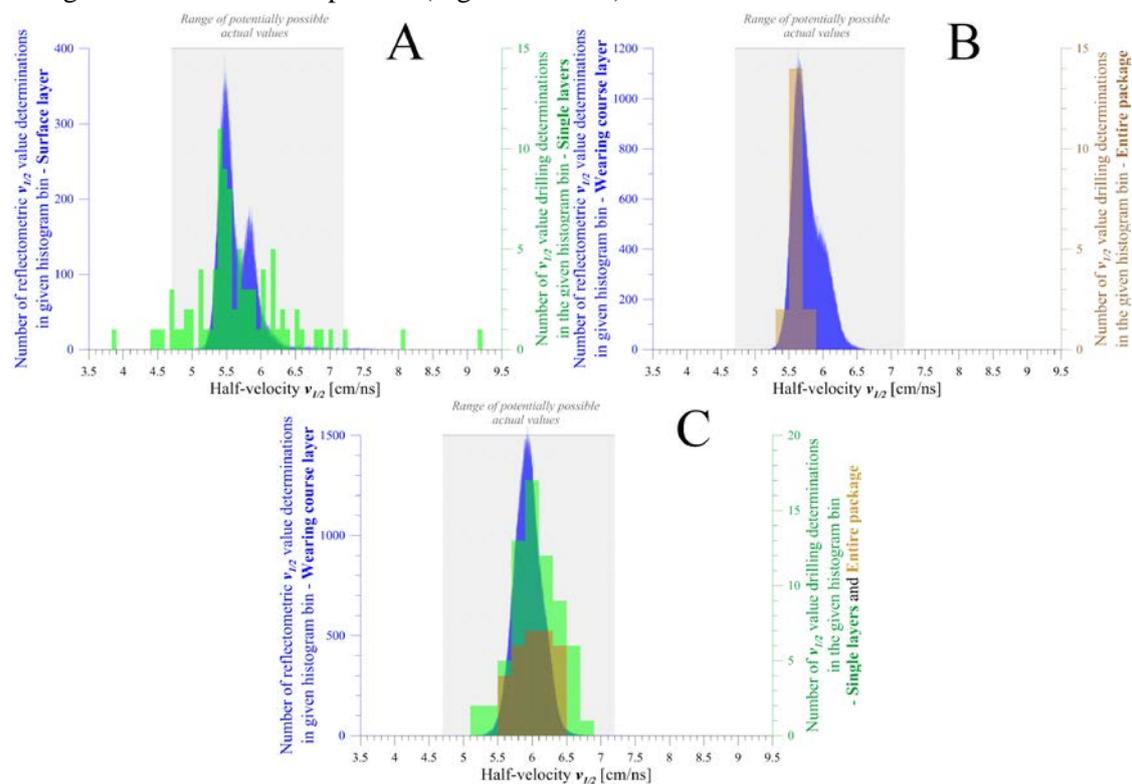


Figure 6. Examples of histograms of half-velocity reflectometric determinations in the upper package layer with the imposed histograms of layer or package half-velocity determination using drillings and wave double-travel times: A) a large set of drill holes in a thin package in the absence of proper control of hole positioning with clearly visible two populations differing in the type of material, B) a set of drill holes with a very good positioning control, C) a large set of drill holes with a very poor positioning control after multiple position verification.

6. Presentation of mapping results

One of the formal ways to document measurements is by means of echograms. They are usually (in the case of mapping or measurements with several antennas) arranged synchronously one over another (Fig. 7). Echograms help imaging a not always unambiguous interpretation of cross-sections and illustrate (in a sketch-like manner) the degree of accordance of thicknesses determined through drillings with a georadar section. When reading echograms, it must be borne in mind that they mostly rely on one optimum velocity determined for a given profile (or the entire road section).

The basic graphic presentation of the results of package thickness mapping is the graphs of variability of the determined thickness along the measurement profiles (Fig. 8). They offer a good insight into the spatial distribution of this parameter.

An important and noteworthy method of visualization of measurement results is the use of thickness histograms of a given road section. Such histograms are helpful in the discussion of the design in the case of new or renovated pavements. In particular, they reveal complications that go with the determination of this parameter in actual structures where the description of thickness with one number and standard statistical concepts does not often reflect the actual situation. Some of these cases shown in Fig. 9B demonstrate the difficulty in measuring thickness in a reliable manner by means of just a few or even single drill holes in randomly selected locations. Such a large span of thickness changes can sometimes lead to misunderstandings.

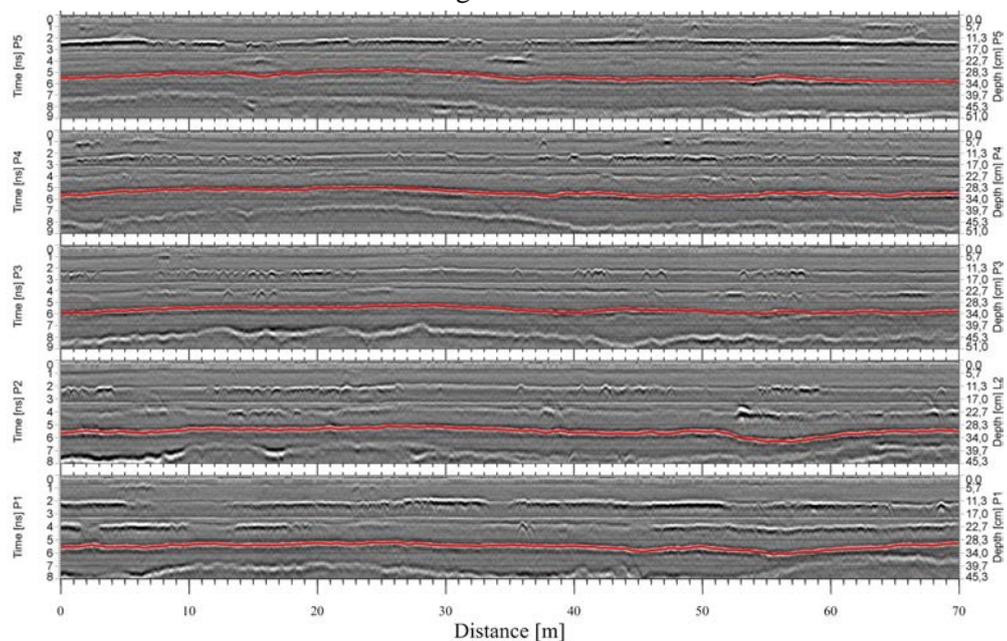


Figure 7. An example of echograms obtained in the mapping of a road section using five parallel GPR profiles.

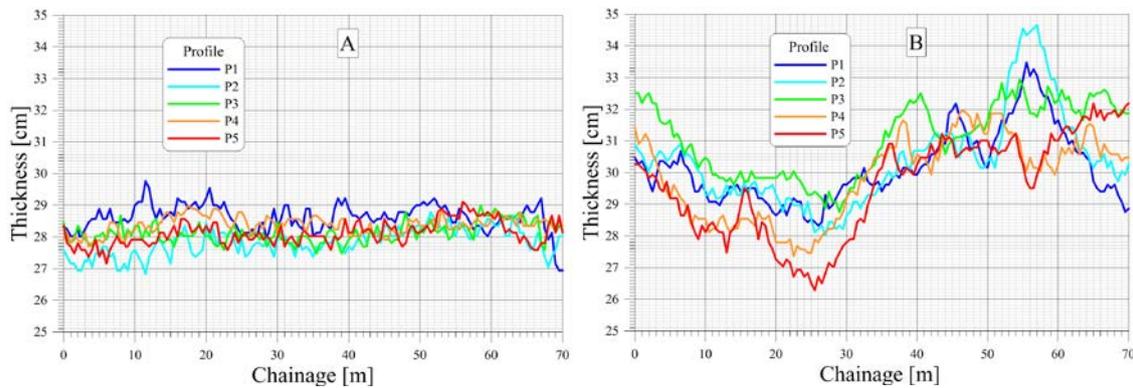


Figure 8. Two examples of collective charts showing the variability of thickness of a package of asphalt layers along mapping profiles.

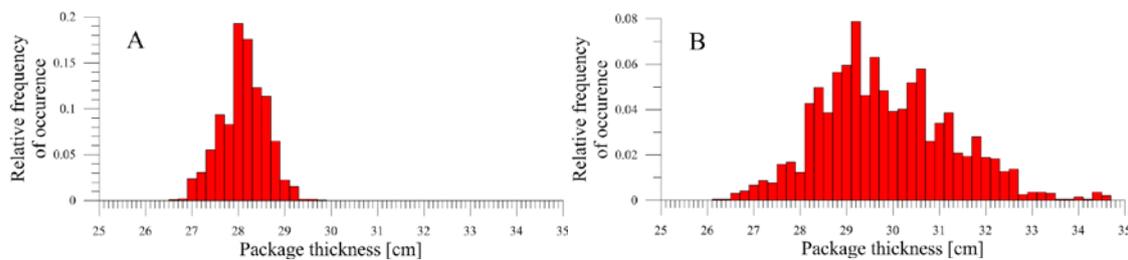


Figure 9. Two examples of histograms of thickness of a package of asphalt layers determined by mapping. A) section with a minor and B) section with significant thickness variation.

7. Summary

The article outlines the methodology of measuring (mapping) the thickness of an asphalt package and its individual layers and discusses the key factors affecting the accuracy and reliability of absolute thickness determination. The following recommendations can be made for such high-precision measurements:

- the use of impulse air-coupled antennas with the central frequency of about 2 GHz,
- calibration of the wave velocity with a strictly controlled location indicated after scanning and initial analysis of the results,
- the application of reflectivity analysis in the preliminary stage of thickness assessment and on sections with a thin asphalt layer package as a substitute method for velocity calibration.

The use of air-coupled antennas with the central frequency of about 2 GHz offers decent capabilities in terms of the depth of penetration, resolution, and accuracy. It also allows the simultaneous application of reflectivity analysis as a preliminary method of thickness assessment.

Based on gather experience, it can be assumed that to calibrate the wave velocity the optimum number of drill holes should be: two on a 300-meter section of a homogeneous pavement and one every further 300 meters of the section length. To control the wave velocity effectively, the number of reference holes should not be reduced to fewer than one per 1 km. The homogeneity of materials forming an asphalt layer package is vital for the proper choice of the number of reference drill holes.

Reflectometric measurements clearly show material differences between road sections. If they are significant, the use of separate velocity calibrations on different sections is recommended. It is therefore a very important control tool in the calibration procedure. However, due to the numerous challenges that go with this method, calibration based on drill holes is preferred. Exceptionally, in the case of very thin packages (less than 10 cm thick) or pavements where drilling is not advisable (e.g. bridges), this method can be used as more effective.

The practice of the discussed measurement method allows the estimation of the thickness with typical uncertainty of thin packets (up to 10 cm thick) at about 0.5 cm and of packages with greater thickness at about 5% in a properly conducted measurement. In the extreme case of a complete absence of estimation of half-velocity, the average value for our region can be referred to, i.e. around 5.5-5.7 cm/ns. However, this can imply an error of even up to 25% of the determined thickness value, also for average values, and an error of 10%+ will be a standard situation.

The described method can be successfully used in tests of asphalt and concrete pavements supporting the acceptance testing phase required in technical specifications, standards and national regulations.

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