

Influence of variability of water content in different states on electromagnetic waves parameters affecting accuracy of GPR measurements of asphalt and concrete pavements

Małgorzata Wutke^{1,*}, Anna Lejzerowicz², Wioletta Jackiewicz-Rek² and Andrzej Garbacz²

¹ TPA Sp. z o.o., Parzniewska 8, 05-800 Pruszków, Poland

² Warsaw University of Technology, Faculty of Civil Engineering, Lecha Kaczyńskiego 16, 00-637 Warsaw, Poland

Abstract. In the paper a water content effect in various states on the variability of the electromagnetic waves parameters is discussed. This variation can affect accuracy and repeatability of asphalt and concrete pavement thickness estimation with GPR method. In case of asphalt pavements, tests were carried out using the air-coupled 1.0 GHz antenna and included three approaches: two on asphalt road and one of asphalt slabs. In the case of concrete slabs, tests were carried out using a ground-coupled 1.6 GHz antenna on two slabs: reinforced and unreinforced. A high variability of the electromagnetic wave parameters was observed depending on moisture conditions. The increase in the humidity of the medium causes a reduction in the propagation speed of the electromagnetic wave (increasing the dielectric constant of the medium), increasing of waves time propagation, decreasing of reflection amplitude and increasing of frequency attenuation, which should be considered when determining the thicknesses of the construction layers. Studies showed that not always higher air humidity, atmospheric precipitation and consequently wet surface indicate a higher dielectric constant of the medium. It can be concluded that not only the humidity and ambient temperature affect the change in the dielectric constant, but also other factors not resulting from the construction of the pavement as well as material microstructure.

1 Introduction

The monitoring and structural evaluation of pavement are required to ensure a good serviceability and to provide adequate maintenance solutions. Ground penetrating radar (GPR) method has appeared as one of the powerful non-destructive technique (NDT) in this field [1]. GPR has been used successfully in a variety of pavements application such as determining its thickness, detecting subsurface distresses, estimating moisture content, detecting various types of voids, as well as to elaborate a repair procedure, optimal from point of view of durability and cost. Proper estimation of pavement thickness is a key point for evaluation of its durability.

Dielectric properties of particular layers of road pavement are important for interpretation of GPR results, e.g. for thickness estimation [2]. One of the main factor influencing electric properties is moisture content in particular pavement layers [3, 4]. Both materials microstructure and weather conditions can affect moisture content in pavement. This variation can affect accuracy and repeatability of asphalt and concrete pavement thickness estimation with GPR method.

The paper presents how the presence of moisture on the surface of asphalt layers affects the dielectric constant of the medium and how the dielectric constant of asphalt layers varies depending on atmospheric conditions, including the presence of rainfall and frozen conditions. It

is also shown how wave propagation time, reflected wave amplitude and the frequency attenuation packet varies depending on the degree of water saturation of the asphalt pavement layers. There are also presented dielectric constant changes of reinforced and unreinforced concrete slabs.

2 Basic principles of GPR

The GPR method is a mobile and non-invasive geophysical method. It is a very-high-frequency electromagnetic technique used to produce high-resolution images. GPR is used for example to detect certain objects in the ground (naturally occurring or man-made), investigate concrete structures and roads, analyze bridge decks or for measurements of asphalt layers thickness. During GPR surveys, a transmitting antenna is used to send a pulse of high-frequency electromagnetic waves of known frequency into the ground. An electromagnetic wave then penetrates the medium where it may undergo transmission, reflection and/or refraction (resulting from a change in electrical parameter). In recorded images (radargrams), the electromagnetic waves that were reflected from the boundaries between deposits characterized by different values of their dielectric constant ϵ_r [1, 2, 3] are analyzed. The ‘quality’ (reflection strength, amplitude) recorded on radargrams depends on the contrast of the electrical properties between the two

media. The electromagnetic wave attenuation coefficient (α) and reflection coefficient (r) can be estimated using following formulas [4]:

$$\alpha = \frac{1.69 \cdot 10^3 \sigma}{\sqrt{\epsilon_r}} \left[\frac{\text{dB}}{\text{m}} \right] \quad (1)$$

where:

α – attenuation coefficient [dB/m];

σ – conductivity [mS/m];

ϵ_r – dielectric constant;

$$r = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \quad (2)$$

where:

r – reflection coefficient;

ϵ_1 – relative permittivity over the reflection border;

ϵ_2 – relative permittivity below the reflection border.

Typically, ϵ_r increases with depth, so generally $\epsilon_1 < \epsilon_2$.

The penetration depth of GPR depends on the frequency of the transmitting antenna and on the properties of the medium. For the same medium, a lower wave frequency enables investigation to a greater depth range, but at the cost of a lower resolution of the measurements [1, 3, 4, 5]. The depth range depends strongly on the dielectric constant of the deposits/materials. Deposits or materials with a high dielectric constant can be distinguished based on the attenuation of the electromagnetic wave. Because water has the highest dielectric constant ($\epsilon_r = 81$) and a high conductivity, the water content adversely affects signal propagation – it influences the rate at which the energy is absorbed, it is reducing the vertical range of GPR prospecting [6]. The dielectric constant (ϵ_r), which is determined by the electrical properties of the solid particles and the content of pore water, increases with increasing moisture content – a more conductive (wet) soil/material will absorb the energy at a far greater rate than a low conductivity (dry) soil/material.

3 Results and discussion

3.1 Asphalt pavement

In case of asphalt pavements, tests were carried out using the air-coupled 1.0 GHz antenna and included three approaches.

3.1.1 The influence of the surface dampness on the dielectric constant of wearing course

GPR measurements were performed five times on a selected 545-meter section of the road. The section on the length from 220 m to 250 m was poured with water. Only for attempts 1-3, an increase in dielectric constants was observed, resulting from passing directly over the area of water retention on surface; for other attempts, no increase in dielectric constants was observed (Fig. 1). This can be explained by the fact that attempts were carried out at a

temperature below zero, and therefore, freezing of water occurred on the surface. The ice dielectric constant is similar to that of asphalt [7], hence the changes after the first three attempts gradually ceased to be visible.

When there is a water film on the surface, some limitations of the GPR method can be observed. The dielectric constant of the first layer calculated from the relationship between the amplitude of the reflection from the ideal reflector (metal plate - calibration) and the amplitude of the reflection from the surface of the structure will be artificially enlarged (due to the presence of a water film) and this may lead to misinterpretation that the tested medium is a moist one. Special attention should be paid when determining the thickness of the layers – an incorrectly determined dielectric constant implies an error in determining the thickness of the layer.

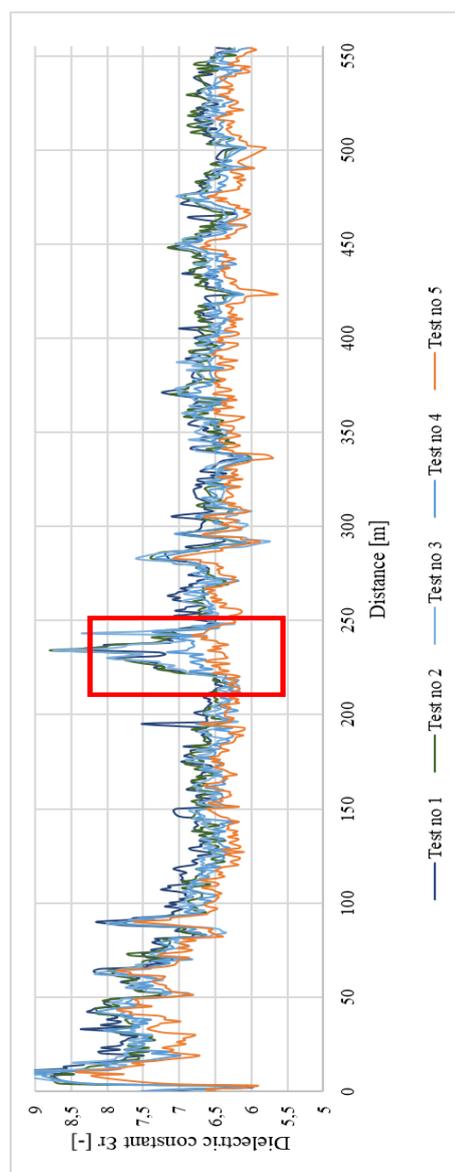


Fig. 1. The influence of the surface dampness on the dielectric constant of wearing course.

3.1.2 Variability of the dielectric constant value of the selected pavement section depending on the atmospheric conditions

During this approach, the repeatability of the obtained results (conducted under identical atmospheric conditions) was determined. In total, in 6 different atmospheric conditions (Tab. 1), GPR measurements were carried out five times (30 measurements in total) on a selected 545-meter section of the road.

Table 1. Conditions during which GPR measurements were carried out

No.	Hours	Air temperature	Ground temperature +10 cm	Ground temperature -10 cm	Rainfall	Air relative humidity [%]
1	11:00-11:30	4.0	4.0	2.8	none	82.0
2	15:30-16:30	5.0	3.2	3.0	none	72.0
3	08:00-08:30	3.6	3.2	3.0	small rain	95.0
4	15:30-16:30	4.7	4.4	3.2	small rain	96.0
5	08:00-08:30	0.8	1.0	3.1	none	96.2
6	23:00-23:30	-7.0	-5.0	1.4	none	92.0

The layer thickness h based on measurements of air-coupled antenna is calculated based on the following relationships [3]:

$$\epsilon_r = \left(\frac{1 + \frac{A_0}{A_p}}{1 - \frac{A_0}{A_p}} \right)^2, h = \frac{ct}{2\sqrt{\epsilon_r}} \quad (3)$$

Where: c is a constant (the speed of light in vacuum), t is the time of the double wave transition to the boundary on which there is a reflection with an amplitude equal to A_0 , A_p amplitude is the amplitude of reflection from the ideal reflector during calibration with a metal plate, ϵ_r is the dielectric constant of the layer through which the wave propagates. While t is a value depending on the actual thickness of the structure, many factors may have an influence on the value of ϵ_r , including factors resulting from atmospheric conditions (e.g. humidity, temperature).

Fig. 2 and 3 shows the variability of dielectric constant values determined as the average value of 5 GPR measurements during 6 different atmospheric conditions (measurement 1 - measurement 6). A high variability of the dielectric constant value was observed depending on atmospheric conditions. In addition, not always higher humidity, atmospheric precipitation and consequently wet surface, cause a higher dielectric constant on the surface. It follows that not only the humidity and temperature, but also other factors, including those not resulting from the construction of the investigated medium, affect the change in the dielectric constant. Such a change of the dielectric constant significantly alters the result of measuring the thickness of the structure, regardless of the actual changes in the thickness value [1].

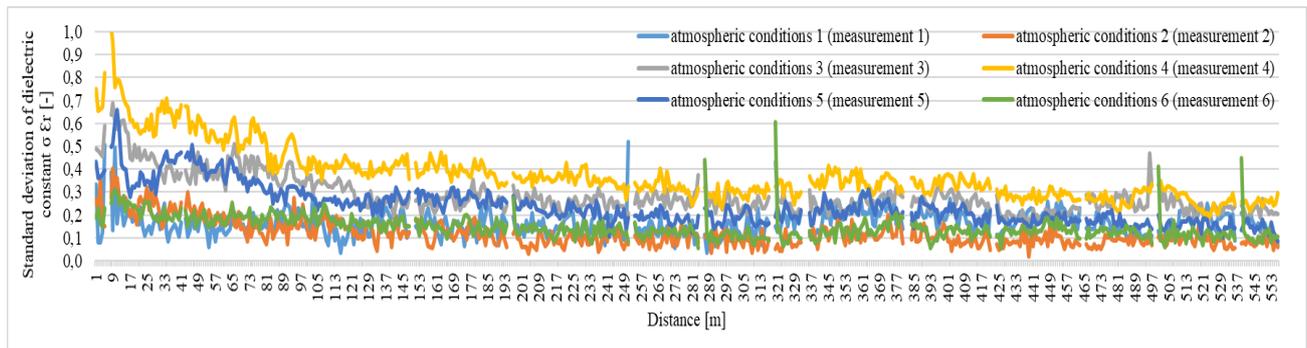


Fig. 2. Variability of the standard deviation of the dielectric constant value of the selected pavement section depending on the prevailing atmospheric conditions

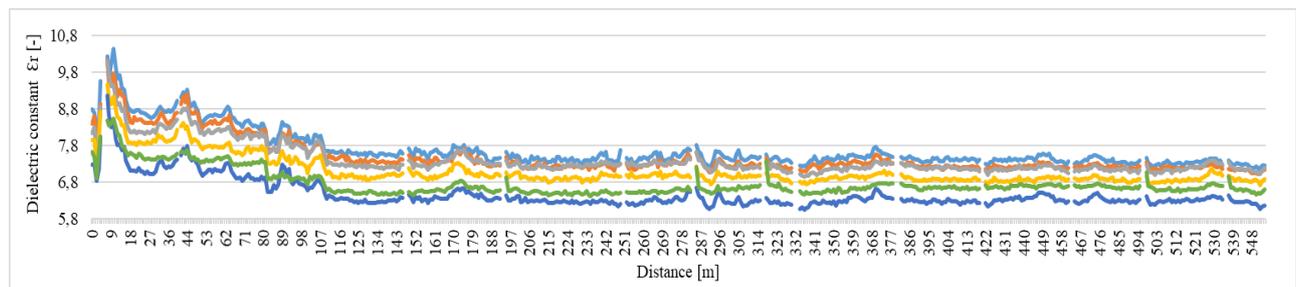


Fig. 3. Variability of the dielectric constant value of the selected pavement section depending on the prevailing atmospheric conditions (for legend see Fig. 2).

Parallel to the influence of external factors shaping the GPR measurement result, the participation of the device itself to the obtained results was also checked. An analysis of standard deviations from 5 GPR measurements performed under the same atmospheric conditions was carried out. Most of them are smaller than 1, which results in a 5% error in determining the thickness of the layer.

3.1.3 Variability of parameters of electromagnetic wave propagation in a natural humidity, a saturated and frozen state

The aim of measurements was to determine the effect of moisture and freezing of the sample on the electromagnetic waves parameters. For this purpose, five asphalt slabs with the dimension 50cm x 50cm x 12cm consisted of three layers: L1 of 4 cm, L2 of 8 cm and L3 of 10 cm have been prepared. Particular layers differ in porosity:

- Slab no 1: 4cm of mastic asphalt (MA 8) with a maximum aggregate size equal 8mm and air void content (V) equal 0%; 8cm of asphalt concrete (AC 16 W) with a maximum aggregate size equal 16mm and air void content (V) around 4-7%; 10cm of asphalt concrete (AC 22 P) with a maximum aggregate size equal 22mm and air void content (V) around 4-7%;

- Slab no 2: 4cm of stone mastic asphalt (SMA 8) with a maximum aggregate size equal 8mm and air void content (V) around 1-3%; 8cm of AC 16 W, V=4-7%; 10cm of AC 22 P, V=4-7%;
- Slab no 3: 4cm AC 8 S, V=2-4%; 8cm of AC 16 W, V=4-7%; 10cm of AC 22 P, V=4-7%;
- Slab no 4: 4 cm BBTM 8, V=12-19%; 8 cm of AC 16 W, V=4-7%; 10 cm of AC 22 P, V=4-7%;
- Slab no 5: 4 cm of porous asphalt (PA 8 S) with a maximum aggregate size equal 8mm and air void content (V) around 18-24%; 8 cm of AC 16 W, V=4-7%; 10 cm of AC 22 P, V=4-7%.

The measurements were carried out on samples in three states: first one, in natural humidity, second one, saturated with water and the last one, frozen. Depending on the moisture content, three analyses were performed: of the frequency attenuation on the bottom of each slab, of the amplitude of the electromagnetic wave reflection from the bottom of each slab and of the time in which the electromagnetic wave reaches the bottom of each slab. Each of the measured parameters affects the electromagnetic wave velocity, and hence - the thickness determined based on GPR measurements.

Based on analyses, the effect of humidity on electromagnetic wave parameters influencing the results of thickness measurements was demonstrated (Fig. 4-6).

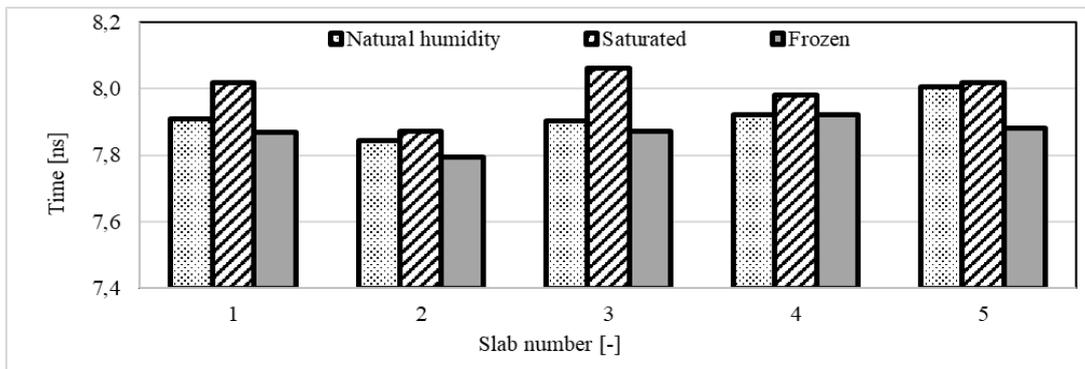


Fig. 4. Variability of time of radar wave penetration depending on water presence.

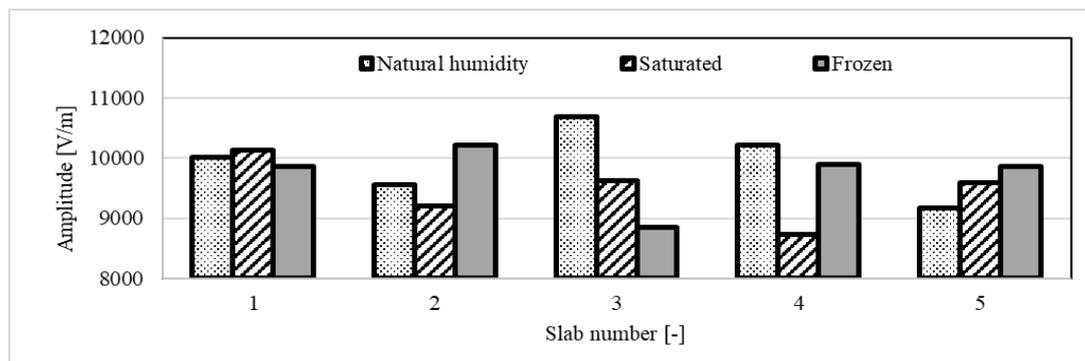


Fig. 5. Variability of amplitude of reflected wave depending on water presence.

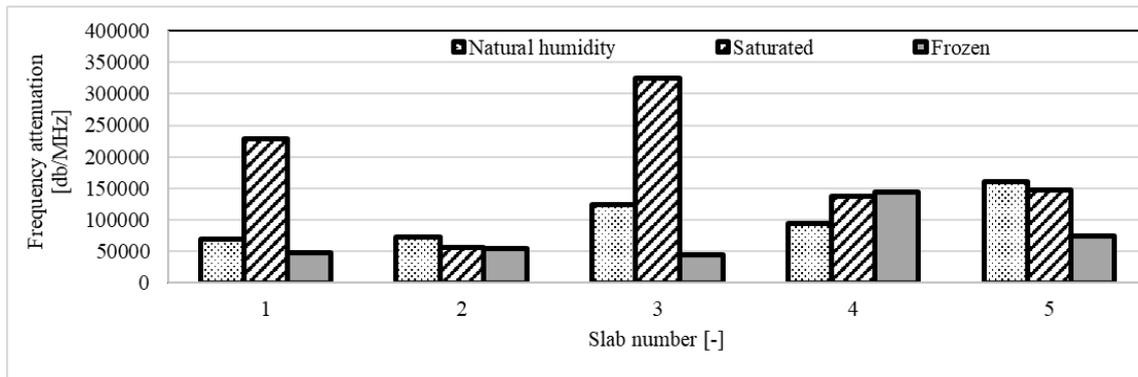


Fig. 6. Variability of frequency attenuation at the slab bottom depending on water presence.

As expected, due to high dielectric value of the water, it was observed that with the increasing of humidity attenuation, the amplitude of the electromagnetic wave reflection from the bottom and the time in which the electromagnetic wave reaches the bottom of each slab decrease. For frozen samples, on the contrary, a decrease in the value of the time of radar wave penetration is noticed. It is explained by the fact that ice has lower dielectric value than water.

For the slab 1 the amplitudes of reflected waves are almost the same at each state: natural humidity, saturated with water and frozen. This is explained by the fact that the first layer of the slab 1 is built from mastic asphalt which has no porosity so there is no water penetration into deeper layers. For slabs 2, 3 and 4 amplitudes are higher in saturated state and this is caused by the fact that water decreases electromagnetic wave energy. Slab 5 which is very porous, has higher reflection amplitude in saturated state. It must be noticed that part of the electromagnetic wave is reflected on the surface, part is transported further, below the slab, and thus the presence of moisture does not only affect the reflection amplitude from the bottom of the slab but also another reflection amplitude. Ice, in general, increases reflection amplitude.

Water causes higher frequency attenuation and freezing decreases this parameter. The largest increases in attenuation caused by saturation is observed for slab 3 which is entirely made of asphalt concrete.

Summarizing, it was observed that with the increasing of attenuation because of humidity, the amplitude of the electromagnetic wave reflection from the slab bottom decrease and the time in which the electromagnetic wave reaches the bottom of each slab increase. For frozen samples, on the contrary, the increase of amplitude and the decrease of time propagation is observed. Changes of these parameters should be considered when determining layer thickness.

3.2 Concrete pavements

In case of concrete pavements GPR investigations were carried out using 1,6 GHz ground-coupled antenna on two samples: one with reinforcement bars and one without. Measurements were carried out in three locations (at the upper and lower edge of the slab and in the middle of the slab), the antenna was placed once perpendicular, once

parallel to the long edge of the slab. Concrete humidity range was from 100% to 80%.

3.2.1 Analysis of the relationship between concrete moisture, wave velocity and dielectric permittivity of concrete

Two slabs (dimensions: 48cm x 25cm 12cm) have been prepared – one with reinforcement bars and one without. After two days under the shutter slabs were taken out and placed in the curing room for 7 days. During this time, they were regularly showered. Then on the side walls of the slabs the resin has been applied and such prepared slabs have been placed in water. Water was absorbed by the capillary network. Slabs were weighed each day until their weight was stable – it took them two weeks to stop absorbing water, they were fully saturated. Such prepared slabs were placed on the tank with water so unidirectional drying up has been achieved.

The GPR measurements were carried out with the use of 1,6 GHz ground-coupled antenna in 3 points on each slab. The antenna was placed in each point perpendicularly (1p, 2p, 3p) and parallel (1a, 2a, 3a) to the longer edge of the slab (Fig. 7). During each GPR measurement the wave velocity in the concrete and the wave velocity in the air was measured. The amplitude of the direct wave, the propagation velocity inside the material and the frequency of the wavelets were analysed.

The propagation velocity of electromagnetic wave in the concrete was calculated in the point 2a, both for the reinforced and non-reinforcement slab. In the paper results only for the non-reinforced slab are presented. The velocity has been calculated as a ratio of time and distance of propagation. As a reference time the first negative peak of the direct wave has been chosen. Time with the appearance of first positive peak on the radargram was taken as the end of propagation. Results calculated for different concrete moistures are presented on Fig. 8.

Dielectric permittivity and the velocity of wave propagation, as well as the amplitude of the direct wave depends on moisture content. With the decrease of water content, an increase of wave propagation velocity and decrease of dielectric permittivity may be observed.

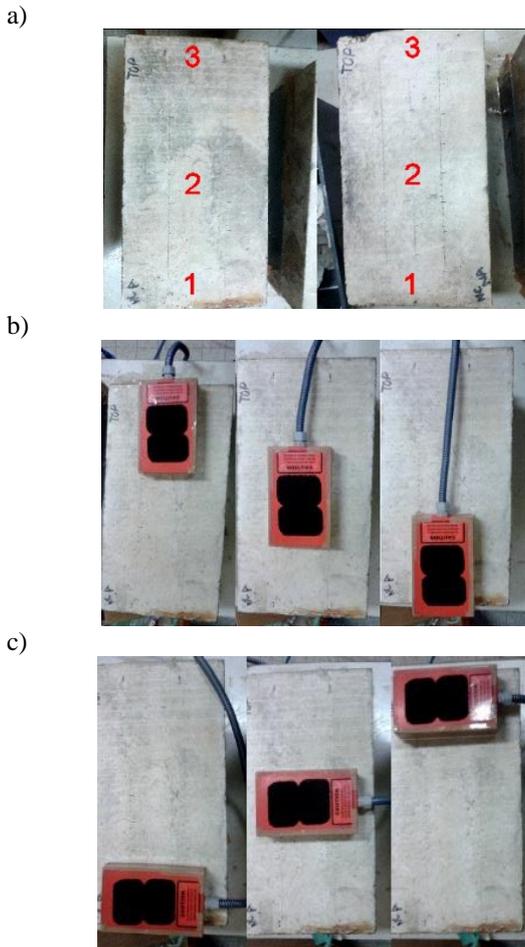


Fig. 7. a) Measurement points on experimental slabs, b) measurements parallel to the longer edge of slab, and c) measurements perpendicular to the longer edge of slab.

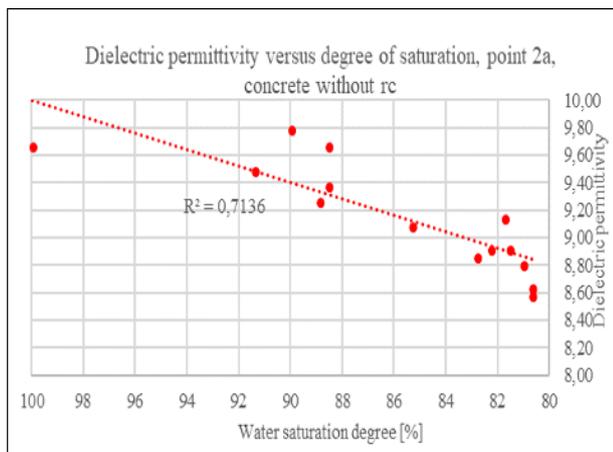


Fig. 8. Dielectric permittivity versus degree of water saturation, point 2a, concrete slab without reinforcement bars.

4 Conclusions

The paper describes the variability of the electromagnetic waves parameters affecting accuracy and repeatability of asphalt and concrete pavement thickness estimation depending on the asphalt or the concrete moisture. It was observed, that the increase in the air humidity and ambient temperature causes:

- increasing of the dielectric constant of the medium (reduction in the propagation velocity of the electromagnetic wave);
- increasing of electromagnetic waves time propagation;
- decreasing of reflection amplitude;
- increasing of frequency attenuation.

Further, studies have shown that not always higher air moisture indicate changes of those parameters. Depending on the air humidity, waves parameters are affected by:

- composition of the measured mixture (especially material porosity);
- stability of emitted and received signal from GPR antenna [9].

All electromagnetic waves parameter changes should be considered when determining the thicknesses of the construction layers, in order to estimate the road thicknesses properly and in effect properly assess the condition of the investigated pavement and elaborate an optimal repair method [9].

References

1. D.J. Daniels, *Ground penetrating radar, 2nd edition* (The Institution of Electrical Engineers, London, United Kingdom, 2004)
2. H.M. Jol, *Ground Penetrating Radar Theory and Applications* (Elsevier, England, 2009)
3. A. Neal, *Earth-Science Review* **66**, 261-330 (2004). J. Karczewski, Ł. Ortyl, M. Pasterniak, *Zarys metody georadarowej* (Wydawnictwa AGH, 2011) (in Polish)
4. J.Lachowicz, M.Rucka, *Diagnostics of reinforced concrete pedestrian bridge using ground penetrating radar method*, Mat.Konf. 'XXVIII Awarie Budowlane', Międzyzdroje (2017), pap.034
5. P. Lamparski, *Prace Geograficzne* 194, 1–115 (2004) (in Polish with English summary)
6. A. Lejzerowicz, S. Kowalczyk, A. Wysocka, *Geologos* **20** (1), 35-47 (2014)
7. T. Saaranketo, *Electrical properties of road materials and subgrade soils and the use of Ground Penetrating Radar in traffic infrastructure surveys* (PhD's graduate thesis University of Oulu, 2006)
8. M. Wutke, *Proceedings of 17th International Conference on Ground Penetrating Radar (GPR2018)* (to be published)
9. M. Wutke, *Proceedings of the conference 'Modern diagnostics and repair of road pavements'*, Kielce (2018) (in Polish) (to be published)