Degraded road pavement survey using GPR

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Abstract

We present the GPR results dealing with flexible road pavements located on embankments. The aim is to evaluate the road damage (particularly the ramified cracks) taking into consideration also other parameters (embankment height and traffic load). The GPR evaluation was carried out on 20 sites selected in the secondary non-urban road network of Atri, a medium-size urban area representative of the Adriatic zone (Central Italy). Stress induced by traffic load generally affects a road section thickness of about 1.5 m from the ground; so a monostatic GPR antenna, with a nominal frequency of 1600 MHz, was used given that its maximum inspection depth corresponds to 1.5 m from the ground. The 1600 MHz antenna has also a quite high-resolution when inspecting road damage. The GPR acquisition was carried out in damaged and adjoining undamaged road sites, to compare the GPR data of the two areas. GPR data analysis was based on the sweep-rectified power approach to evaluate the radar signal attenuation curve vs. depth, which permitted us to single out different road types of damage and to discuss the factors which caused them.

Keywords: durability of road pavements, degraded roads, GPR monitoring and inspection, maintenance and rehabilitation strategies, preventive maintenance

1 Introduction

We report the results carried out by using GPR technique on flexible road pavements built on embankments. The goal was to find correlations between the type of paving deterioration, the embankments height, the traffic load and the results obtained from the GPR campaign. Previous studies have always evaluated different types of paving deterioration with a reduced number of GPR scans. The results were interesting but not definite, due to their extremely small number [1]. During the current research, to increase our data we acquired five GPR measurements for each variable evaluated (type of paving deterioration, embankments height, traffic load). With regards to the type of deterioration inspected, the survey was conducted only on the ramified cracks (also called spider or alligator cracking) that represent one of the five types of bearing capacity structural defects regarding flexible road pavements [2], [3].

2 The research goals

The research goals were to carry out a survey with the GPR technique of degraded road pavements with a single type of deterioration, carried out on the embankments. The ramified cracks (RC) deterioration analyzed were selected to represent the worst conditions. Longer fractures measuring 5 m and wider than 5 mm were identified and, regarding the extension of degraded areas, more than 5 m^2 extended pavements were identified. Regarding the influence of the height of the embankments and the intensity of the traffic, were considered pavements consisting of high embankments (HE), a height of > 4 m, and on low embankments (LE), a height of < 2 m, and pavements subject to heavy traffic load (HT), with average daily traffic > 4000, and low traffic load (LT), with average daily traffic < 1000. Once again dealing with traffic loads, a further verification was performed which took into consideration the diversity of the fleet of vehicles in transit on the roads surveyed, in order not to neglect the effect of heavy traffic. This verification was not focused on the average daily traffic load, but rather on the equivalent standard axle loads (ESALs - each of the 120 KN) per year. The evaluation confirms the results obtained in the first study and identified the following traffic load classes: heavy traffic load (HT) with > 400,000 ESALs/yr and low traffic loads (LT) with < 4,000 ESALs/yr. Therefore, the inquiry was performed on twenty sites chosen to be representative of the different combinations of the variables analysed. The same sites were identified on the non-urban road network located close to Atri. Be informed that the studied area is placed at an altitude of 500 m above sea level and is characterized by cold winters. The superstructures of the evaluated roads are constituted by flexible road pavements which have similar layers, with the following thicknesses: layer of foundation in granular mixture: 30 cm, base layer in bitumen mixture: 10 cm, binder layer: 6 cm and surface layer: 4 cm, both consisting of a bituminous concrete. Therefore, the superstructures on average have a total thickness of 50 cm. The GPR surveys were carried out to perform a quantitative analysis through the examination of the GPR signal attenuation curves with the depth (the rectified power method). An antenna module with a nominal frequency of 1600 MHz was used, which is a type of evaluation that is quite reliable if directed at a depth of up to 1.5 m. This choice was made based on the effect, due to the stresses induced by traffic on embankments, to a maximum depth of about 1.5 m, developing, however, in the most accentuated form on an average in the first 50 cm of the superstructure [4]. In this current study, we used a 1600 MHz butterfly antenna manufactured by Systems Engineering - IDS (Pisa). It is a portable, monostatic type, non-dispersive antenna and is characterized by linear polarization, low directivity and limited bandwidth.

3 Analysis with sweep rectified power method

As it is known, the propagation of an electromagnetic field is described by the Maxwell equations, in which the constant of attenuation α appears, which expresses the amount of energy that is absorbed by the intersected layers. Remember that the larger the void ratio of the evaluated material the greater the attenuation of the radar signal and the lower the attenuation constant is α [5].

Therefore, by determining precisely the α attenuation constant, it is possible to obtain a positive evaluation of the depth of the signal penetration itself. Since the goal of our study is to evaluate the importance of structural defects, we decided to focus the evaluation on a maximum depth of 1.0 m from the road pavement. This choice was made because the effect, due to the stresses induced by traffic on embankments, to a maximum depth of about 1.5 m, developing. However, in the most accentuated form on an average in the first 50 cm of the superstructure and spreading, with a still evident and easily seen result, for an additional 50 cm. Therefore, the theoretical reference road section was schematized in two portions: the first, 50 cm (S1), representing the superstructure and the second, an additional 50 cm (S2) representative of the portion of embankment laid on soil which is affected by the traffic [6]. This choice was in line with the demands that the antenna resolution of GPR had adopted (1600 MHz). Another fundamental assumption adopted in the model was that layers S1 (road pavement) and S2 (subgrade) are considered homogeneous on average. This assumption does not accurately reflect the reality, especially for the S1 layer, given the granulometric variety, specific weight and form that characterize the materials used in road pavements. The sweep rectified power analysis, carried out in our study using software created by IDSGred by Ingegneria Dei Sistemi, graphically represents the average trend (straight line attenuation) energy absorbed by the ground portion of the embankments placed between 50 and 100 cm (S2). Through this interpretation of the rectified power diagrams, you can trace the α attenuation angle that graphically represents the angle that envelopes the R^2 regression line of power, forms with the x-axis which, in turn, indicates the depth from the road surface. Regarding the surveys carried out in our study, please note that the analysis was carried out considering two contiguous stretches in length equal to 1.5 m belonging respectively to a damaged area and an undamaged area from degradation and as not to present specific abnormalities, such as vitiating the comparison. The relative diagrams for the two contiguous sections surveyed (both damaged and undamaged area) were included in the same graph to highlight their differences. The red coloured diagrams are related to the degraded road sections; while those of green coloured diagrams belong to the intact portions [7]. By making comparisons between attenuation corners of damaged areas ($α_d$) and undamaged ($α_u$), it is expected that if the difference between these values ($Δα = α_d-α_u$) tends to zero, then the probable cause that generated the deterioration of paving is attributable to phenomena of fatigue or thermal shrinkage. These phenomena are due to horizontal tensile stresses that develop in the S1 layer of the road pavement (Fig. 1a). In fact, in this case, in the S2 layer the energy curves are almost coincident, which means that the background terrain relating to the two examined road sections, display the same degree of densification and there are no compactions in place (Fig. 2). If instead, $Δα ≠ 0$ the probable cause that triggers the degradation of the road pavement is attributable to the compaction change of the embankment (S2 layer) due to the action exerted by traffic. In this circumstance, we must make a further distinction between the case in which $Δα > 0$ and the case in which $Δα < 0$. In the first, the energy curves for the damaged areas (red) are at a lower energy content than those undamaged (green). This means that the deteriorated areas are more compacted of the not deteriorated areas. More precisely, the energy curves for the damaged areas (red) are positioned beneath those undamaged (green), and this confirms the fact

that a lower power consumption level corresponds to an index of lesser void ratios (Fig. 3).
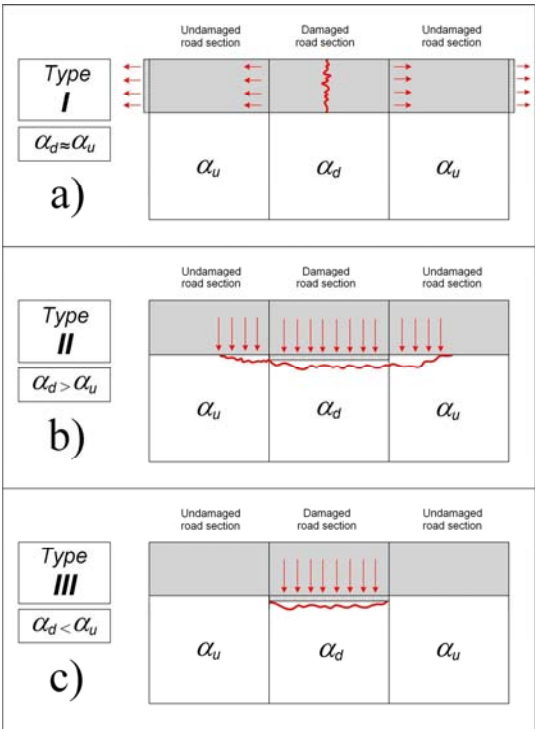

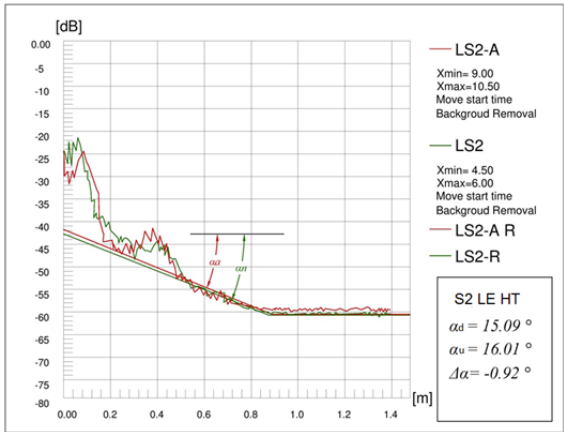**Figure 1.** Diagram illustrating the three types of deterioration
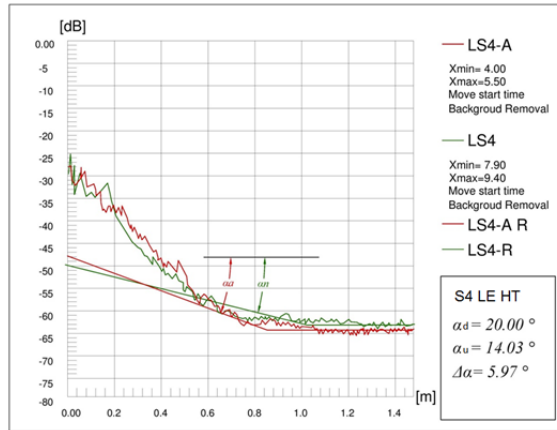

Figure 2. Example of the Δα = 0 case

Figure 3. Example of the Δα > 0 case

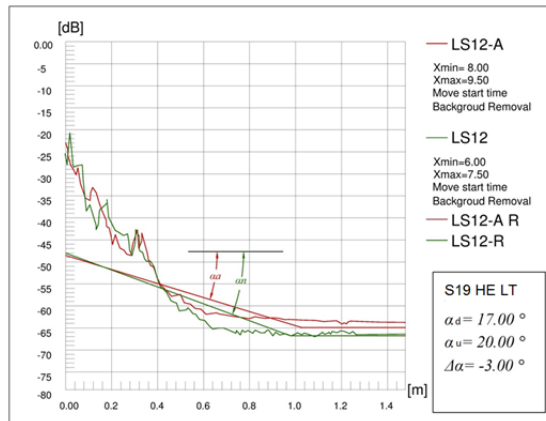**Figure 4.** Example of the Δα < 0 case

Therefore, the degradation process is no longer in place in the deteriorated area, while the areas that are not deteriorated will tend, over time, to assume the same level of densification of damaged areas. Then the entity of degradation will tend to not remain confined in the deteriorated area but to expand in the neighbouring areas (Fig. 1b). In the second, the curves for the damaged area (red) are at a higher energy content than those which are undamaged (green), and that the deteriorated areas are less non-deteriorated compacted areas. More precisely, the energy curves for the damaged areas (red) are positioned above those undamaged (green), and this confirms the fact that at a power level absorbed corresponds a higher void ratio greater (Figure 4). Therefore, the degradation process is still going on in the deteriorated area and continues until it reaches the densification level of the area not deteriorated; for this, the degradation will remain confined in the area (Fig. 1c).

4 Survey results

We analyze the results of surveys carried out with GPR in the twenty sites chosen which are representative of the various combinations of the variables studied. In this regard, it is noted that the accuracy in the interpretation of radargrams is a function of the antenna resolution and sampling the electromagnetic signal; in our case they are respectively of 1 cm and of 1024 samples per second. Furthermore, the resolution in the power sweep diagrams is of 1 dB for the signal attenuation (y-axis), and of 4 cm from the road surface to the depth (x-axis). This approach provides a detailed resolution to be able to evaluate areas up to 1 cm^2 in a thickness of road pavement/embankments up to the depth of 1.5 m (Figs. 2, 3, 4). With the assistance of the sweep rectified power analysis, we proceeded to the evaluation of signal attenuation angles is in damaged sections (α_d), and in those undamaged (α_u), to which was followed by the evaluation of the variation of the attenuation ($\Delta\alpha$). In Table 1 are reported, the various combinations tested, the values of the attenuation constant α and the index $\Delta\alpha$ calculated. Please note that any survey is characterized by a code indicating, for the type of deterioration evaluated (ramified cracks RC), the height of the embankment (HE, LE) and traffic load (HT, LT), according to the preceding paragraphs. The analysis of the results made it possible to divide the types of degradation in two categories: the first consists of the resulting deterioration due to problems inherent in the road pavement layer (layer S1), and the second consists of the interesting deterioration of the subgrade layers (layer S2). The deterioration in the first category (breaking in S1 layer) have provided values of $\Delta\alpha$ content in a range, respectively, of -2 < $\Delta\alpha$ < +2. In this regard, the analysis of the values reported in Table 1, it was found that for road sections characterized by high traffic (HT) both low embankments (LE), with 3 sections of 5, and especially with high embankments (HE) with 5 sections out of 5, we were obtained the same types of results concerning the rupture in layer S1. For the findings, we can state that, in the light of the considerations set out in the preceding paragraph, the deterioration caused in the S1 layer (Figs. 1a, 2) are normally generated by horizontal tensile stresses due to fatigue or thermal shrinkage affecting the surface layers of the road pavement. Generally, the road pavement rupture depends from the undersize of layers respect to the traffic loads. As said, we can deduce that the soils used in the embankments (up to 1.5 m deep) are not, in this case, the cause of no damage of the cracking type. From the analysis of the results in the first category (breaking in S1 layer), it is clear a high repeatability resulted from the values obtained from the measurements with the GPR (100% with HE and HT sections and 60% with LE and HT sections), demonstrating that GPR is reliable for evaluation of deteriorated road surfaces and provides consistent results. Regarding the deterioration of paving in the second category (rupture in the S2 layer), however, they were recorded values of $\Delta\alpha$ included in an interval of -6< $\Delta\alpha$ <+6. As found, it can be said that the deterioration regarding the layer (S2) are generated by the sudden density change of the subgrade terrain produced by the vehicle traffic (embankments soil compaction). It is noted that, in the case of low traffic (LT) and low embankments (LE), for 3 sections of 5 were recorded the highest values of $\Delta\alpha$ and all with a positive sign.

Table 1. The different values of α_d and α_u measured and the index $\Delta\alpha$ calculated

Height embankment	Traffic load	α_d	α_u	$\Delta\alpha$	Damaged layer
LE	HT	16.09	16.01	0.08	S1
LE	HT	15.09	16.01	-0.92	S1
LE	HT	15.08	16.01	-0.93	S1
LE	HT	20.00	14.03	5.97	S2
LE	HT	10.00	15.91	-5.91	S2
HE	HT	10.12	10.01	0.11	S1
HE	HT	16.00	15.01	0.99	S1
HE	HT	20.00	18.03	1.97	S1
HE	HT	17.00	16.00	1.00	S1
HE	HT	17.00	16.01	0.99	S1
LE	LT	18.01	18.07	-0.06	S1
LE	LT	18.00	18.01	-0.01	S1
LE	LT	20.00	14.00	6.00	S2
LE	LT	15.00	12.03	2.97	S2
LE	LT	19.00	13.03	5.97	S2
HE	LT	17.00	20.03	-3.03	S2
HE	LT	14.00	18.00	-4.00	S2
HE	LT	15.00	18.00	-3.00	S2
HE	LT	17.00	20.00	-3.00	S2
HE	LT	20.00	18.00	2.00	S2

This means that the problems inherent in the compaction are not limited to the layers close to the substrate but extend throughout the height of the embankments up to the support surface of the natural ground. In the case of low traffic (LT) and high embankments (HE), were recorded, for 4 sections of 5, the highest values of $\Delta\alpha$ and all with negative sign. This means that the problems of compaction are limited to the layers close to the substrate and remain confined in the already deteriorated areas. Also in this case the results obtained show a high repeatability with 80% in the case of homogeneous results HE and LT and 60% in the case of LE and LT showing that it is a reliable methodology for evaluation of road pavements deteriorated even with different conditions of traffic and

embankments. In conclusion, it can be stated that combinations of HE variables with both HT and LT provided results with the highest repeatability. While the combinations of LE variables, with both HT and LT variable provided results with a less than acceptable repeatability, this shows that low embankments are conditioned by unpredictable external factors such as, for example, the influence of the support pavement of natural terrain positioned close to the road pavement.

5 Conclusions

The results of a GPR survey conducted on degraded road pavements built on embankments is presented. It was evaluated only one type of deterioration (ramified cracks) and was carried out a survey on a large sample (five surveys) for each of the evaluated variables (height of embankments and traffic load). These pavements have been identified on secondary roads of the non-urban area of the city of Atri. The evaluation of the attenuation curves of the radar signal detected from the road pavement, performed by the sweep rectified power method, allowed us to determine the attenuation constant α. Through the comparison of the attenuation constant α detected on two adjacent longitudinal sections, belonging respectively to a damaged portion (α_d) and to an undamaged stretch (α_u), made it possible to trace the causes of the degradation of the analyzed pavements. The results, taken from a large sample, showed high repeatability to demonstrate that the methodology can be trusted to evaluate deteriorated road pavements with different traffic conditions and heights of embankments.

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