DEGRADATION OF ROAD PAVEMENTS BUILT IN CUTTING SECTIONS EVALUATED WITH GPR

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ABSTRACT

Structural degradation of road pavements has a considerable impact on traffic safety. Roadway surface defects or discontinuities make driving uncomfortable and increase chances of accidents. GPR is an effective and non-destructive technique to discover and trace the causes of road pavement damages so characterizing road integrity.

The paper shows the findings of a GPR survey carried out on degraded road pavements built in cutting sections. The survey was expected to find correlations between: (i) types of damage, (ii) depth of cutting sections, (iii) traffic load and (iv) GPR scan results. Five types of damages, inducing loss of load bearing capacity, were investigated: (i) transversal and longitudinal cracks, (ii) only longitudinal cracks, (iii) only transversal cracks, (iv) ramified cracks and (v) failures. To determine the impact of cutting depth and traffic load on road pavement degradation, the survey focused on high (depth > 4 m) and low (depth < 2 m) cuttings, as well as on heavy traffic (average daily traffic > 4000) and low traffic (average daily traffic < 1000) road pavements.

Twenty sites were chosen in the area of L'Aquila (central Italy), describing the different combinations of the variables to be analysed. Road integrity was evaluated by a GPR quantitatively analysis (GPR signal attenuation vs. depth), using a 1600 MHz antenna. It investigates media till a depth of 1.5 m which is also the maximum depth of influence of the induced traffic stress. GPR scans were first made on the degraded part of the road and then extended to its nearby unaffected part. The results carried out from the two sets of scans (affected and unaffected parts) were compared in order to identify GPR signal changes. These changes made it possible to trace the causes of the damage to the road pavement vs. cutting depth and traffic load.
Keywords: GPR, 1600MHz antenna, structural defects, degraded road pavement

1. INTRODUCTION

1.1 The management of road pavement

The conditions of the road pavement, its roughness and evenness and its lack of localized or diffuse failures have a crucial impact on driving comfort and traffic safety. Consequently, degradation of road pavements plays a dramatic role in road safety, directly or indirectly. If damages to road pavements are not prevented with adequate maintenance, they may significantly increase the likelihood of accidents and the severity of damages.

Thus, a correct approach to road management emphasizing safety and preventing accidents requires a comprehensive plan with the following key elements: (i) identification and classification of road pavement degradation; (ii) analysis of the scenario of possible causes; (iii) definition of the methodology to be followed and of the Best Available Technology for identifying the causes of the pavement degradation; (iv) prediction of the evolution of degradation over time; (v) analysis of the severity of road pavement damages and of their evolution over time in terms of road safety; (vi) identification of the most effective and efficient rehabilitation projects.

The paper addresses these problems with reference to flexible road pavements located in the secondary non-urban roads in the area of L'Aquila (central Italy). In view of the recent breakthroughs of research in this sector (Benedetto & D'Amico 2006, Chun-Lok et al. 1992, Saarenketo & Scullion 2000), the causes of degradation of these road pavements were investigated with advanced GPR techniques because it shows many advantages among which quickness of measurements, low cost, reliability of diagnosis, possibility to investigate the causes of degrade.

In fact, usually the road damage is easy to localize, but the causes of damage are always difficult to identify, because they are frequently hidden in subgrade or under the ground layer. This lack of information can compromise the works for rehabilitation, because if the cause is not completely removed the effect occurs again.

One of the most relevant causes of damage is often referable to water seepage in subgrade or clay intrusion in sandy subgrade. Sometimes the cause can also be referred to a deficit or an excess of soil compaction. The aim of this study is to show the consistency of GPR diagnosis regarding to these hidden conditions.

1.2 The GPR method

Getting an in-depth understanding of a road pavement means identifying its type, size, materials, as well as the thickness of its layers and the mechanical properties of its constituents. The study of road pavement composition may rely on conventional methods, such as boreholes, or on non-destructive geophysical techniques.

In the past few years, GPR, a non destructive technique, has been extensively used thanks to its high efficiency, fast speed, non-destructiveness and limited interference with pedestrian and vehicle circulation.

GPR can emit radio frequency signals in the typical range of 10-2000 MHz and record the echoes radiated by the objects contained in the medium or by the layers of different type which make up road surfaces.

A transmitter generates a signal with a nanoseconds frequency which is radiated by a broadband antenna. The energy pulse propagates to the road pavement at a given velocity: when the pulse meets a layer whose dielectric properties are different from the ones of the overlying layer, then part of the energy is reflected by the layer, while the remaining energy crosses it. At the surface, the antenna receives the reflected signals.

The amplitudes of the reflected waves provide information on the dielectric properties of the investigated layers. Interface echoes and echo spacings (time intervals that the pulse takes to cross the layers) can be identified on the receiver-recorded trace. From these time intervals, layer thickness can be determined.

In brief GPR diagnosis is found on the analysis of the difference between the transmitted radar signal and the received one. In this way electromagnetic and other physical properties of investigated media can be identified (Bucchi et al. 2002; Gatti & Liuzzi 1998).

In the study reported in this paper, use was made of a 1600 MHz monostatic antenna to get information on flexible road pavements of non-urban roads network of L'Aquila town. Antenna, data collection and processing software were developed by Ingegneria dei Sistemi (Pisa, Italy).

1.3 Degradation of flexible road pavements

Defects in flexible pavements are indicative of road distress and impaired efficiency. They may be due to poor performance of constituent materials, errors in design, engineering or construction, environmental and climate factors, as well as to particularly heavy traffic. Two types of defects may be distinguished: functional and structural (SITEB 2004).

Functional defects express superficial degradation of the wearing course of pavement; this degradation reduces both vehicle grip to the road and regularity of the road surface, jeopardizing traffic safety.

Factors responsible for this type of degradation, about skid resistance problems, include: levelling (or polishing) of aggregates; surface exposure of bitumen (known as bitumen blooming); detachment of aggregates. Smoothness problems comprise: longitudinal undulations, transversal undulations (more commonly called ruts); hollows or bulges; dips on extensive surfaces; edge cracking.

Conversely, structural defects arise on the supporting courses of the superstructure. They are due to deterioration of its load-bearing capacity and have major repercussions on pavement durability, if they are not timely cured. Defects of this type are surface cracks and breaks; more recurrently: transversal and longitudinal cracks, longitudinal cracks only, transversal cracks only, ramified cracks (spider or alligator cracks) and failure (CNR 1988, SHRP 1993, VSS 1991).

The research study reported in the paper was confined to road pavements with structural defects compromising their load-bearing capacity. Figure 1 gives five examples of these defects in the above-mentioned order.

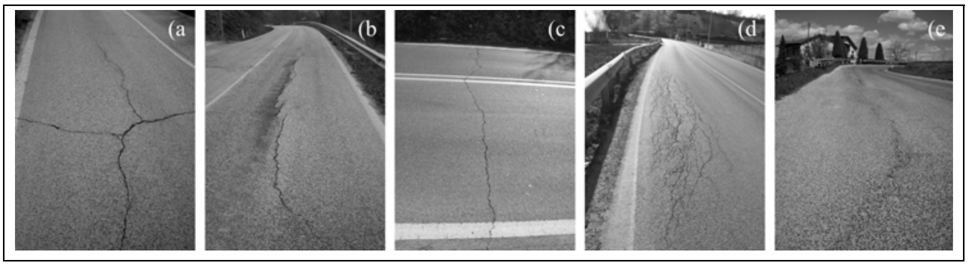

Figure 1 Structural defects examined in this study: a) transversal and longitudinal cracks, b) longitudinal cracks only, c) transversal cracks only, d) ramified cracks, e) failures.

It is worth reviewing the potential factors which trigger structural degradation and reduce the load-bearing properties of flexible road pavements. These factors may be related both to problems occurring upon construction and to effects supervening during road use.

In particular, permanent deformation of the subgrade and of the loose and bound granular materials making up the pavement, which takes place during construction, may result from a combination of different (and usually concurrent) causes: unevenness of the subgrade - supporting course; poor workmanship in the placing of layers; poor or uneven compaction; incorrect finishing (water puddles); non-homogeneous thickness. The repeated-stress deformations, due to vehicular traffic, generally originate in the loose granular layers and subgrade of the pavement. They are caused by the use of unsuitable materials, such as: granular mixes with crushable aggregates; granular mixes with excess of fines; granular mixes with plastic fines; aggregates of inappropriate grain size; plastic or compressible subgrades.

During road use, also bituminous-concrete layers may contribute to structural degradation of the road surface for the following reasons: presence of crushable aggregates; inappropriate grain size curve; bitumen unsuitable for the climate and traffic conditions of the site; wrong dosing of bitumen; inadequate thickness (under sizing); bituminous concretes that are too stiff with respect to the underlying non-bound layers (Benedetto & Angiò 2002a, b, Benedetto & De Blasiis 2001).

2. THE RESEARCH STUDY

2.1 Goals

GPR techniques were applied to investigate degraded pavements of roads built in cutting sections. The study was expected to find correlations between types of degradation, depth of cuttings, traffic load and GPR findings.

As to the types of degradation, the study was restricted to the above-mentioned five types of structural defects (impaired load-bearing properties): longitudinal and transversal cracks (LTC), longitudinal cracks only (LCr), transversal cracks only (TC), ramified cracks (RC) and failures (F). All the analysed defects were selected according to the worst conditions (high degree of degrade), i.e. the investigated cracks are more than 6 m length and 0.3 cm wide, and the investigated failures are more than 5 m^2 extensive.

As for the impact of cutting depth and traffic load, the study took into consideration pavements built in high cuttings (HC – depth above 4 m) and on low cuttings (LCu – depth below 2 m), as well as surfaces exposed to heavy traffic (HT) with an average daily traffic > 4000 and to low traffic (LT) with an average daily traffic < 1000.

For traffic load, account was also taken of the differences in the vehicles that travel on the investigated roads and namely of the effects of heavy traffic. This verification was not focused on the average daily traffic but rather on equivalent standard axle loads per year. The investigation substantiated the results obtained in the first study and identified the following traffic load classes: heavy traffic (HT) with > 100,000 ESALs/yr and low traffic (LT) with < 15,000 ESALs/yr.

The study covered twenty sites, representing the different combinations of the investigated variables. The sites were selected on non-urban secondary roads in the territory of the city of L'Aquila.

The investigated roads were as follows: Mausonia provincial road; state road no. 615; Roiense provincial road; Bagno provincial road. The area under study lies at an altitude of about 800 m above sea level and has a long and cold Winter season.

All the investigated road superstructures have flexible pavements and practically equivalent courses, with the following thickness values: granular-mix foundation course 30 cm; bitumen-mix base course 10 cm; binder course 6 cm and surface course 4 cm, both in bituminous concrete. Thus, the superstructures have an average overall thickness of 50 cm.

GPR scans made it possible to quantitatively analyze the curves of radar signal attenuation vs. depth (sweep power). In particular, use was made of an antenna array with a nominal frequency of 1600 MHz. This type of investigation is fairly reliable down to a depth of 1.5 m. The choice was based on the consideration that traffic load stresses, on road cuttings, reach a maximum depth of about 1.5 m and are more pronounced in the first 50 cm of the superstructure.

GPR scans were divided in two stages: in the first, the scans covered the damaged road section; in the second, the scans were extended to a nearby undamaged road section. The comparison of the results from the two sets of scans (damaged vs. undamaged road sections) showed variations between the recorded radar signals. These variations led to trace the causes of the investigated types of degradation in the damaged road section vs. cutting depth and traffic load (Colagrande et al. 2007a, b).

2.2 Results

Two 1.5 m-long road sections (one damaged and the other undamaged) were scanned with the 1600 MHz antenna. The selected undamaged road section did not have anomalies which might bias its comparison with the damaged road section.

The radargrams of the two road sections were included in the same graph, so as to highlight their differences. The black diagrams refer to damaged road sections, while the grey ones concern undamaged road sections. In both cases, the peaks in the diagrams reflect the presence of voids. Figures 2-6 display the graphs of sweep power under the various investigated conditions. Each figure has a code identifying the type of degradation (LTC, LCr, TC, RC, F), the cutting depth (HC, LCu) and the traffic load (HT, LT), as specified in the previous paragraph. Based on the analysis of the graphs, pavement degradation was divided into two categories: crack-type degradation (LTC, LCr, TC) and extensive degradation (RC and F).

With regard to the first category, all the pairs of diagrams in each graph practically coincide and the final value of the sweep power difference between the two curves always lies below 3 dB. In this connection, it is worth making an additional consideration about the three types of degradation which were recorded in road sections exposed to heavy traffic (HT) and built on both high (HC) and low (LCu) cuttings (Figs 2a, 2b, 3a, 3b, 4a, 4b). Indeed, in the graphs, the signals of the two diagrams have fragmented deviations down to depth of about 50 cm (thickness of the superstructure). These deviations mainly depend on the fact that one curve refers to a degraded superstructure, while the other concerns an unaffected superstructure. In contrast, in the remaining part of the diagram (X-axis: from 50 to 150 cm), these deviations are practically parallel and spaced by 2 dB on average. The black diagrams (damaged road sections) lie below the grey ones (undamaged road sections) in these two cases: Figure 4a TC-HC-HT and Figure 4b TC-LCu-HT. In the other four cases, shown in Figure 2a LTC-HC-HT, Figure 2b LTC-LCu-HT, Figure 3a LCr-HC-HT and Figure 3b LCr-LCu-HT, the signals are reversed.

Since a difference in the absorbed power value generally reflects a difference in the void index (higher power corresponds to a higher void index (Benedetto & Benedetto 2002), it can be presumed that, in the first two cases, the damaged zones beneath the superstructure (at a depth over 50 cm) have experienced settlement and consequent densification of the subgrade materials. Hence, when traffic load is heavy (HT), superficial cracks are supposed to arise, above all, from inadequate (e.g. crushable) subgrade materials or to their poor compaction. In the other four cases with reversed signals might mean that, although degradation is already present, soil settlement in the damaged zones is still under way and will eventually cause further damage.

It should also be added that, always in the case of heavy traffic (HT), another factor triggering this type of degradation is rupture by fatigue of bituminous-concrete layers, because the load-bearing courses of the road are undersized with respect to actual traffic load or because the bituminous-concrete layers are too stiff as against the clearly too deformable underlying layers.

For the same three types of crack, a similar consideration should be made about road sections that are exposed to low traffic (LT) and that lie on both high (HC) and low (LCu) cuttings (Figs 2c, 2d, 3c, 3d, 4c, 4d). In this case too, the signals of the two curves display small fragmented deviations down to a depth of about 50 cm (thickness of the superstructure), while they practically match in the remaining zone (at a depth of about 50 to 150 cm). The near-perfect match between the two curves describing the above-mentioned remaining zone infers that the soils involved are in the same situation. These findings indicate that cracks may be due to thermal shrinkage of the surface courses in bituminous concrete, since the investigated roads are located in fairly cold areas. The data in the diagrams suggest that, in case of roads exposed to low traffic (LT), the subgrade soils (down to a depth of 1.5 m) are not responsible for any crack-type degradation. The above does not rule out that the cracks identified in the various investigated cases may arise from a combination of the above-mentioned causes.

These causes have a different impact, depending on whether they are concurrent, combined or cumulated.

As to the second category of degradation (RC and F), all the pairs of diagrams pertaining to heavy traffic (HT) and both high (HC) and low (LCu) cuttings (Figs 5a, 5b, 6a, 6b) are practically very similar to those obtained for the first category (cracks) under the same traffic conditions (HT). As a matter of fact, the two diagrams have fragmented deviations down to a depth of approximately 50 cm (thickness of the superstructure). Instead, in the remaining zone (depth of approximately 50 to 150 cm), the deviations are practically parallel and spaced by 5 dB on average. This sharp difference reflects different soil compaction between the damaged zone and the undamaged one, which generates failure upon the passage of vehicles, especially heavy ones. Hence, the same considerations made about crack-type degradation apply and have even more relevance here. In Figures 5a and 5b, the final part of the black diagram (damaged road section) lies above the grey diagram (undamaged road section). This is tantamount to saying that the damaged zone is less compact than the undamaged, thereby suggesting that pavement cracking and failure due to the densification of subgrade materials are still ongoing. The diagrams of Figures 6a and 6b have an opposite configuration, i.e. the final part of the black diagram is below the grey one. In this instance, the damaged zone is more compact than the undamaged one, thus indicating that the failure has been completed. However, it should not be neglected, especially for cracks of type RC (involving a much wider surface) that one of the main causes, when traffic is heavy, is fatigue rupture of the bituminous-concrete courses or their excessive stiffness with respect to the too deformable underlying layers.

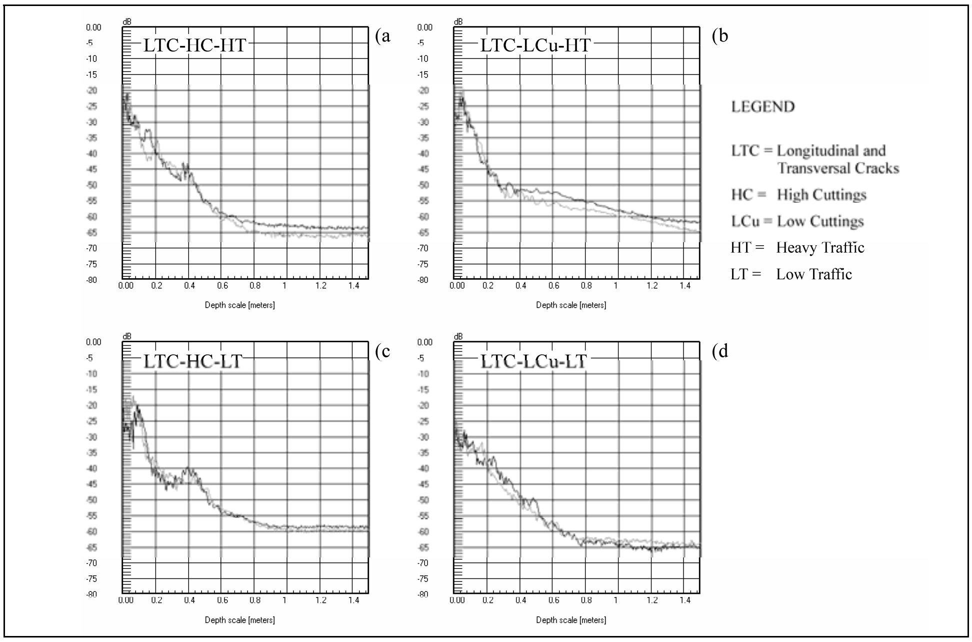

Figure 2 Sweep power diagram (LTC case study).

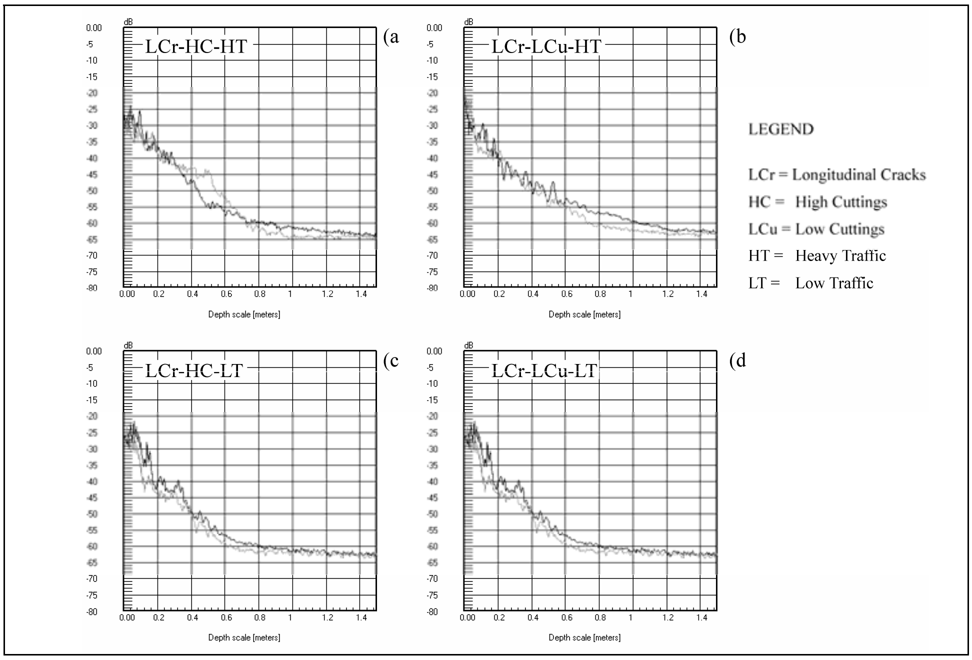

Figure 3 Sweep power diagram (LCr case study).

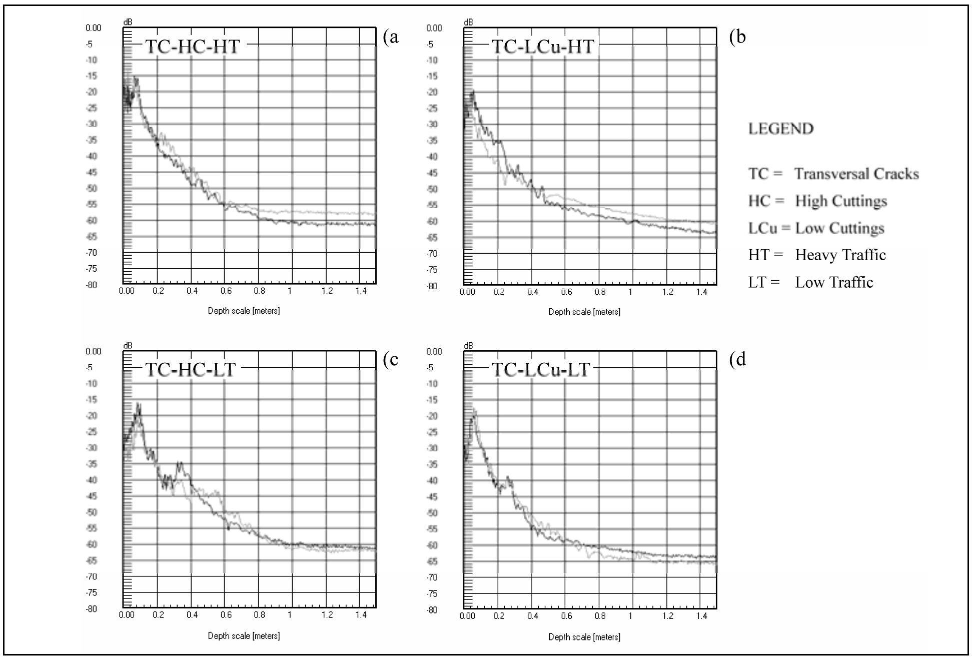

Figure 4 Sweep power diagram (TC case study).

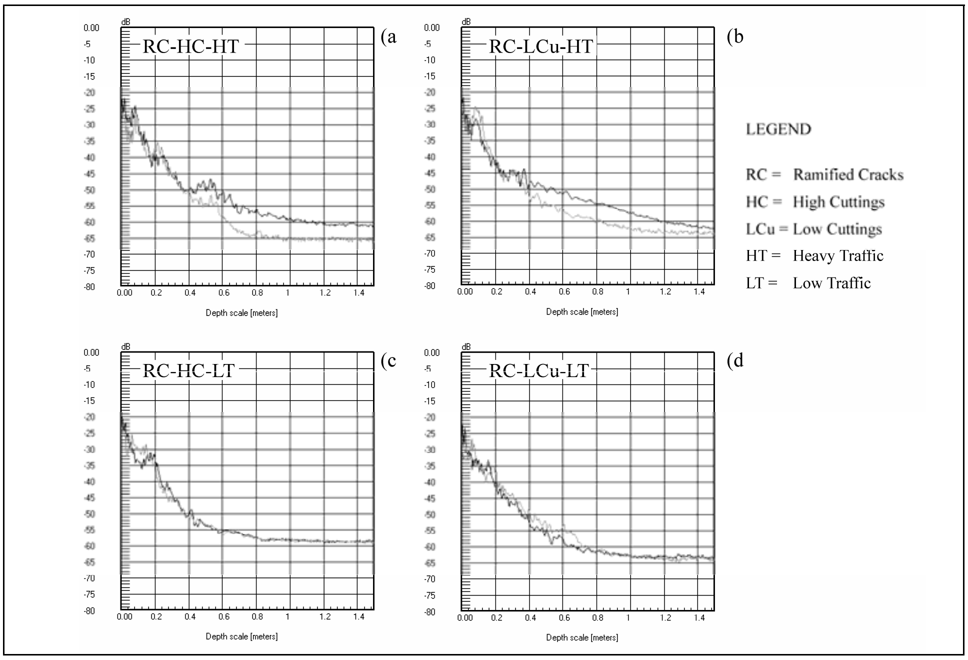

Figure 5 Sweep power diagram (RC case study).

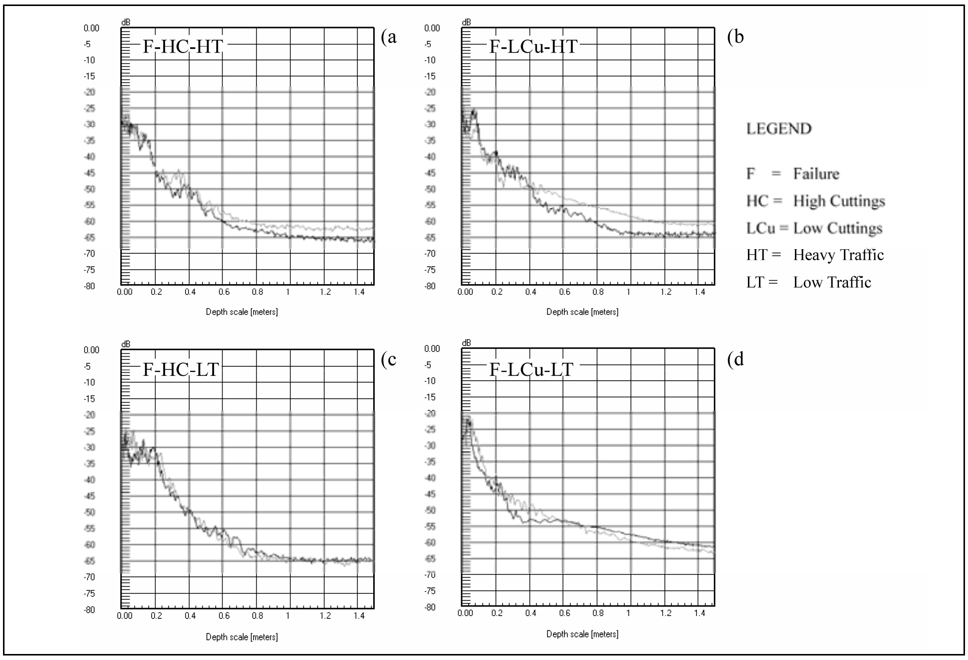

Figure 6 Sweep power diagram (F case study).

Figures 5c, 5d, 6c, 6d exhibit the diagrams pertaining to low-traffic (LT) road sections (second category of degradation – RC and F – and high and low cuttings – HC and LCu). In zones lying beneath the superstructure, curves practically match, as in the case of crack-type degradation. Therefore, the previous considerations apply here too. In particular, for degradation of type F (generally affecting a very wide surface) one of the main causes is due to a inadequately subgrade building or repairing. Another cause is due to a poor workmanship during the building of superstructure layers consequently leading to their non-homogeneous thickness.

Table 1 specifies the points (and their depth from road level) where the two radar signals (damaged road section, black graph; undamaged road section, grey graph) diverge. In the Table, the cases where the two curves overlap are called “overlap”.

If these findings are validated by more extensive research on more diversified situations, they may have useful applications in detecting and tracing the evolution of structural degradation due to a load-bearing deficit.

Table 1 X-axis coordinates (i.e. their depth in cm from road level) where the two radar signals (damaged and undamaged road section) diverge. Data from Figures 2-6.

Defect	High Traffic		Low Traffic	
	HC	**LCu**	**HC**	**LCu**
LTC	60	40	overlap	overlap
LCr	70	60	overlap	overlap
TC	60	50	overlap	70
RC	40	40	overlap	overlap
F	50	40	overlap	70

3. CONCLUSIONS

The paper describes the results of a research carried out with GPR techniques. The study was conducted on degraded roads pavements built in cutting sections. The investigated roads are part of the secondary non-urban road network of the territory of L’Aquila (central Italy). The study was intended to find correlations between the following variables: types of degradation, cutting depth, traffic load and GPR scan results. Five types of degradation, inducing loss of load-bearing capacity, were investigated: transversal and longitudinal cracks, longitudinal cracks only, transversal cracks only, ramified cracks and failure.

To determine the impact of cutting depth and traffic load on road pavement degradation, the study was focused on high (depth > 4 m) and low (depth < 2 m) cuttings, as well as on heavy traffic (average daily traffic > 4000) and low traffic (average daily traffic < 1000) road pavements. Twenty sites were selected, representing the different combinations of the variables to be analyzed. Road integrity was evaluated by a GPR quantitative analysis (GPR signal attenuation vs. depth), using an antenna array with a nominal frequency of 1600 MHz, which is effective down to a depth of 1.5 m. This choice originated from the fact that traffic load has an effect on the road pavement down to depth of about 1.5 m.

GPR scans were first made on the damaged part of road and then extended to its nearby undamaged part. The results obtained from the two sets of scans (damaged and undamaged parts of road) were compared in order to identify GPR signal changes. These changes made it possible to trace the causes of the damage to the road pavement vs. cutting depth and traffic load. GPR scans were aimed to analyzing the diagrams of signal power absorption vs. depth (sweep power) and thus at identifying some common characteristics among the investigated types of degradation, under different conditions of traffic load and cutting depth.

In particular, in heavy-traffic road sections lying on both high and low cuttings, the signals in the two diagrams had small fragmented deviations down to a depth of roughly 50 cm (thickness of the superstructure). These deviations are mainly due to the fact that one curve refers to a damaged superstructure and the other to an undamaged one. Conversely, for the remaining zone (depth of about 50 to 150 cm), the deviations are practically parallel and spaced by 2 dB on average for crack-type degradation and by 5 dB for degradation covering more extensive surfaces (ramified cracks and failures). Since a difference in power value is usually indicative of a difference in the void index, the damaged zones beneath the superstructure (lying at a depth of over 50 cm) are likely to have experienced settlement and consequent densification of subgrade materials.

Hence, when traffic load is heavy, whatever the cutting depths, the causes of surface degradation can be summarized as follows: (i) fatigue rupture of bituminous-concrete layers owing to undersized load-bearing courses with respect to actual traffic load; (ii) excessive stiffness of bituminous-concrete layers vs. the one of underlying layers, which are clearly too deformable; (iii) presence of inadequate subgrade materials (e.g. crushable materials or excessive clay); (iv) poor soil compaction during subgrade construction.

With regard to low-traffic road sections on both high and low cuttings, the signals in the two diagrams had small fragmented deviations down to a depth of roughly 50 cm (thickness of the superstructure), whereas they practically coincided in the remaining zone lying at a depth of about 50 to 150 cm. The near-perfect match between the two curves defining the remaining zone of the investigated cutting sections indicate that the soils involved are in the same situation. These findings suggest that deformation is likely to be due: (i) to a inadequate building of subgrade-supporting plane; (ii) to a poor workmanship during building of superstructure layers leading to their non-homogeneous thickness and (iii) to thermal shrinkage of the surface courses in bituminous concrete, as the investigated roads are located in fairly cold areas.

The above does not rule out that degradation detected in the investigated cases may depend on a combination of the above-mentioned causes, which have a different impact, depending on whether they are concurrent, combined or cumulated.

At this stage, no generalization can be made. Nonetheless, the study has confirmed that GPR evaluation of degraded pavements is possible after adequate calibration of instruments and electronic tools.

Based on the results of this study and on the good correlations obtained between GPR signals and the characteristics of the investigated road pavements, it can be stated that all-GPR approaches may be developed in the future for detecting damage to road pavements built in cutting sections. Indeed, the GPR technique is non-destructive, easy to use, fast and cost-effective.

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