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RESEARCH **Open Access**

Evaluation of the Depth of Deteriorations in Concrete Bridge Decks with Asphalt Overlays Using Air-Coupled GPR: A Case Study from a Pilot Bridge on Korean Expressway

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Abstract

In this recent work, a ground penetrating radar (GPR) technique was proposed to evaluate the deteriorated depth of concrete bridge decks with asphalt overlays in the Korea expressway network. Air-coupled GPR was utilized in the measurement of the relative permittivity of concrete on bridge decks with asphalt overlays and the electromagnetic (EM) wave attenuation of the concrete cover of top reinforcing bars (rebars) in the pilot bridge in public service. In addition, 13 core samples were obtained from the bridge deck to carry out a detailed survey that includes visual inspection of the deterioration and measurement of chloride content with depth. The validity of the GPR technique was examined by comparing it with the results of the field investigation. Moreover, the correlation of the deteriorated depth with either the relative permittivity or EM wave attenuation was established. Results show that a GPR signal analysis method based on a dual-criteria (relative permittivity and EM wave attenuation) is more effective in analyzing the deterioration characteristics and evaluating the deteriorated depth of concrete bridge decks with asphalt overlay compared to the analysis method based on one of the two GPR properties. Results of the field test are considered to be significant wherein it establishes a relationship between the GPR property and deterioration characteristics of the bridge decks. Moreover, results show the practical applicability of the GPR technique in evaluating the deteriorated depth of the bridge decks with asphalt overlay.

Keywords: ground penetrating radar, relative permittivity, wave attenuation, bridge deck, deteriorated depth

1 Introduction

With the increasing economic development, the expansion of the expressways in Korea has reached a total extension of about 4500 km comprised of more than 40 expressways in 2017. Currently, there are 9244 bridges under the Korea Expressway Corporation (KEC) with a total extension length of 1165 km and an average service period of 13 years. Between 1991 and 2002, a total of 4176 bridges (45% of all expressway bridges) was completed during the intense expressway investment period. Presently, only 309 expressway bridges (3%) have been in service for over 30 years but it is estimated to increase to up to 1975 (21%) expressway bridges within the next 10 years. This would imply a greater need in the maintenance and monitoring as well as higher repair costs of the expressway bridges in Korea.

The continuous increase in the maintenance repair cost at the field sites is attributed to the aging of facilities since 2000. About 100 billion KRW has been allotted as the average annual budget for the maintenance and repair, which is not sufficient to cover all the damages. In the past 4 years (2014–2017), KEC has requested an annual budget of 107.2 billion KRW for the maintenance and repair of structures. However, the actual allocated amount was only 56.2 billion KRW, which is about 52%

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of the total requested budget. The difficulty in securing a satisfactory maintenance and repair budget is a common problem of most industrialized nations such as the US, the UK, Japan, Korea, etc. (ASCE 2013; MLIT 2013; Lee et al. 2015b).

Several problems encountered in the maintenance and repair of bridges in Korea are the damage of asphalt overlays of bridge deck and subsequent deterioration of the concrete (Lee et al. 2015a). The rapid deterioration of the bridge decks, among the other components of the bridge structure, is due to the direct exposure to traffic loads and harsh environmental conditions. Annually, about 30–50 billion KRW, which is more than 30% of the structural maintenance and repair budget of KEC, is being spent on bridge decks and overlays. From the perspective of the road managers, it is of great importance to evaluate the current condition of the bridge decks for the safety of public users and the efficient budget operation. Unlike with the bare concrete bridge decks, visual inspection of the concrete bridge decks with asphalt overlay is challenging because of the asphalt concrete layers. Destructive tests, such as core extraction, are performed in order to acquire reliable information on the concrete condition of the bridge decks such as chloride penetration profile and rebar corrosion. However, the tests are labor-intensive, time-consuming and cannot be applied ubiquitously over the entire bridge deck area.

Ground penetrating radar (GPR) technique is a nondestructive test and evaluation (NDT/NDE) method, which is popularly used in the laboratory and field evaluation of the condition of bridge decks. During the operation of the GPR system, a transmission antenna is installed perpendicular to the road surface where an electromagnetic (EM) wave is emitted via underground. Figure 1 illustrates the possible path of the radar wave emitted from the GPR antenna. Some of the energy of the EM wave is transmitted through the layers of asphalt and deck concrete while the remaining EM waves are reflected from the boundary at different permittivity. The reflected EM wave is detected by the receiving antenna of the GPR system and stored for data analysis. The analysis of the reflected EM wave allows the detection of underground cavities, rebar location, and layer thickness (Morey 1998). ASTM D 6087-08 (2008) is the standard test procedure that would provide information on the condition of the asphalt-covered concrete bridge decks by the energy attenuation method. The method is based on the principle that the area of deteriorated concrete with greater chloride concentration and water content would exhibit higher energy attenuation than the sound area. Many researchers have verified that the in situ testing method is effective in assessing the condition of concrete bridge decks (Maser and Bernhardt 2000; Cardimona et al. 2000; Maser 1990). Previous studies have investigated the process of enhancing the accuracy of the reflected EM wave attenuation method (Dinh et al. 2016; Hasan and Yazdani 2014; Tarussov et al. 2013; Barnes et al. 2008). Moreover, several researches have demonstrated the feasibility of GPR as an in situ NDE method to evaluate the depth of chloride-induced deterioration of concrete in bridge decks (Varnavina et al. 2015). In that research, a relationship between GPR

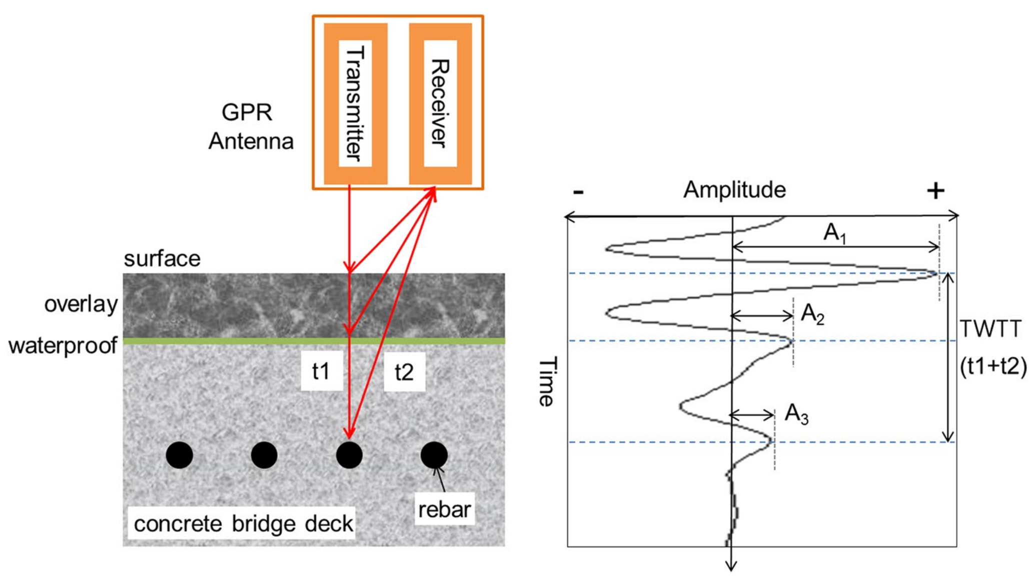

Fig. 1 Illustration of GPR scanning on a concrete bridge deck and a possible path of EM waves in asphalt-covered concrete bridge decks.

attenuation and deteriorated depth was established based on the data acquired from the bare concrete bridge deck.

As early as 1990s, KEC has implemented the use of GPR equipment to evaluate the surface and/or near-surface of pavements in Korean expressways networks. In addition, the applicability of GPR mounted on a vehicle as a tool for the assessment of the condition of expressway bridge decks has been explored (Suh et al. 1998, 2000). The evaluation of bridge deck concrete with asphalt overlays is mainly based on the relative permittivity value of the interface between the asphalt concrete layers and concrete deck (or referred to as an A/C interface). As a rule of thumb, an area near the concrete surface in bridge decks with a relative permittivity value of 12 or above is considered as a deteriorated area (or potentially deteriorated area). A high value of permittivity is attributed to high water content that could lead to significant degradation of concrete by freeze–thaw action. The signal interpretation method using GPR has been demonstrated to be effective in the evaluation of concrete deterioration of deck surface under asphalt overlays (Suh et al. 2009, 2010). However, relative permittivity is not sufficient to assess the condition of concrete in bridge decks with asphalt overlays (Rhee and Choi 2017), especially in evaluating the corrosive environment of rebars and/or early-stage of chloride-induced deterioration in concrete. To overcome this limitation, a pilot-scale testing of the bare concrete bridge deck using the attenuation method was carried out (Rhee et al. 2016). However, the variation of the GPR signal attenuation in the concrete bridge deck with asphalt overlays strongly depends on the condition of structures that includes the thickness and soundness of the asphalt concrete layers, and waterproof performance of the A/C interface. Consequently, it is difficult to evaluate the deterioration occurring within the concrete using this method. It was determined to be difficult to evaluate the deterioration of bridge decks with asphalt overlay based on only one of the EM wave characteristics (i.e. relative permittivity or wave attenuation).

The main purpose of this study is to propose a GPR technique in evaluating the deterioration of concrete bridge decks with asphalt overlays in the Korea expressway network. Air-coupled GPR was used to determine the relative permittivity of the concrete bridge deck with asphalt concrete and the attenuation of EM waves of concrete cover of top reinforcing bars (rebars) in the pilot bridge in public service. In addition, 13 core samples were obtained from the bridge deck to carry out a detailed survey that includes visual inspection of the deterioration and the measurement of the chloride contents with depth (KS F 2713 2002). The validity of the GPR technique was examined by comparing it with the results of the field investigation. Moreover, the correlation of the deteriorated depth with either the relative permittivity or the EM wave attenuation was established. The present work would examine the effectivity of the GPR signal analysis method based on dual-criteria in determining the deterioration characteristics and the depth of the bridge decks with asphalt overlays.

2 Background: EM Properties of Concrete Using GPR

2.1 Relative Permittivity of Concrete

In GPR applications, the relative permittivity, ε_r, is one of the critical parameters used to determine the propagation velocity of an EM wave (V_m) in a material. Knowing that the propagation velocity in air (C_{air}) is 300 mm/ns, the V_m in a material can be approximated using the following equation:

$$V_{\mathrm{m}} = \frac{C_{\mathrm{air}}}{\sqrt{\varepsilon_{\mathrm{r}}}} \quad (1)$$

Subsequently, the depth of a reflector (d) is calculated using Eq. (2) (Balanis 1989)

$$d = \frac{C_{air}T}{2\sqrt{\varepsilon_r}} \quad (2)$$

where T is the two-way travel time of an EM wave in a material (TWTT; $t_1 + t_2$, see Fig. 1); t_1 is the travel time of an incident EM wave from a transmitter to a rebar; and t_2 is the travel time of a reflected EM wave from a rebar to a receiver. It is necessary to obtain the reliable relative permittivity of the material in order to accurately assess the condition of the targets embedded in the media.

In this study, the relative permittivity of concrete was measured by the surface reflection method using GPR (Maser and Scullion 1991). The method determines the relative permittivity of concrete bridge decks with asphalt concrete layers near the concrete surface (ε_{conc}) that is calculated using Eq. (3) (Saarenketo 2006; Maser 1991);

$$\sqrt{\varepsilon_{conc}} = \sqrt{\varepsilon_{asp}} \times \left[\frac{1 - \left(\frac{A_1}{A_p}\right)^2 + \left(\frac{A_2}{A_p}\right)}{1 - \left(\frac{A_1}{A_p}\right)^2 - \left(\frac{A_2}{A_p}\right)}\right] \quad (3)$$

where A_p indicates the amplitude of an incident EM wave (in this study, the amplitude of the reflected wave from a steel sheet plate); A_1 and A_2 are the amplitude of the reflected waves from the air-asphalt surface and from the A/C interface, respectively (refer to Fig. 1); and ε_{asp} denotes the relative permittivity of asphalt concrete that is determined using Eq. (4):

$$\sqrt{\varepsilon_{asp}} = \frac{1 + A_1/A_P}{1 - A_1/A_P} \quad (4)$$

Prior researchers have proposed a theoretical model for evaluating the effective relative permittivity of deteriorated concrete (Fares 2012; Tsui and Matthews 1997). In the model, concrete was assumed to be a material composed of three phases: solid (fine and coarse aggregates, hydrated and non-hydrated cement), liquid (water, chloride solution) and gas (air). In general, deteriorated concrete is characterized by its enhanced porosity and/or microcracks, which increases the concrete's permeability. Since the relative permittivity of water is 81, deteriorated concrete would contain a higher amount of water. Therefore, the relative permittivity of deteriorated concrete would be greater in comparison to solid concrete.

2.2 Signal Attenuation in Bridge Decks

The EM waves emitted from a GPR antenna diminish as it moves through the concrete material. The attenuation of EM waves depends on electric conductivity, media and magnetic relaxation, and material and dielectric damping of concrete (Olhoeft 1984). Generally, sound concrete exhibits good waterproofing performance, low water content, and can be regarded as a low-loss material irrespective of conductivity. The attenuation of the EM waves transmitted to the solid concrete is governed by the dielectric damping based on the constant antenna frequency and the relative permittivity of concrete. Thus, a decrease in the amplitude of EM waves is observed with increasing the depth of a reflector in concrete. In contrast, deteriorated concrete is characterized by its higher permeability due to enhanced porosity and microcracks, which allows conductive materials such as moisture and chlorides to penetrate the concrete. This leads to a more reduced amplitude of EM waves in deteriorated concrete of bridge decks (Cassidy 2009). The conductive loss has been widely used as a measure of the severity of deterioration in concrete bridge decks using the GPR survey.

Theoretically, the total attenuation of reflected EM waves (δ_{rebar}) from the top layer of rebars in concrete decks with asphalt overlays is described as follow:

$$\delta_{rebar} = \delta_{overlay} + (\delta_{cover\_depth} + \delta_{cover\_conductive}) \tag{5}$$

where $\delta_{overlay}$ refers to the attenuation due to the asphalt overlays; δ_{cover_depth} signifies the attenuation due to geometric and dielectric loss of the concrete cover; and $\delta_{cover\_conductive}$ denotes the attenuation due to conductive loss of the concrete cover. In this study, δ_{rebar} and $\delta_{overlay}$ were indirectly measured using the relative GPR reflection amplitude, which are the reflection amplitudes from interfaces in concrete bridge decks normalized by the amplitude of the reflected waveform from a steel sheet plate A_p (Eqs. (6) and (7)):

$$\delta_{rebar} = 20\log_{10}\frac{A_3}{A_P} \tag{6}$$

$$\delta_{overlay} = 20\log_{10}\frac{A_2}{A_P} \tag{7}$$

where A_p refers to the reflection amplitude from a steel sheet plate, and A_2 and A_3 refer to the peak amplitudes of reflected EM waves from the A/C interface and the top surface of rebar, respectively (see Fig. 1). In addition, it is essential to adjust the effect of concrete cover of actual rebars on the GPR attenuation for a more reliable estimation of $\delta_{cover\_conductive}$. In this study, the concrete cover effect was determined based on the recommendations of previous researches (Dinh et al. 2016; Romero et al. 2015; Barnes et al. 2008), and will be discussed further in Sect. 4.2.

3 Bridge Status and Survey Method

3.1 Pilot Bridge

The surveyed pilot bridge ('J' bridge) in this study is a pre-stressed concrete box girder (PSCB) bridge completed in 1998. The bridge has two traffic lanes with 150 m extension and 12.6 m width (Table 1, Fig. 2). The penetrating waterproof materials were sprayed on top of the bridge deck concrete. This was then covered with two layers of asphalt concrete.

The 'J' bridge is located at PyeongChang on Yeongdong expressway between Incheon and Gangneung. Furthermore, this location is considered as the coldest and snowiest region in Korea that has an average temperature of about − 10 °C between December to March (KMA 2018). Therefore, a great deal of deicing chlorides has been sprayed in this heavy snowfall and cold region. Pre-wet salt was prepared by mixing rock salt and calcium chloride before spraying on the roadway (mass ratio: 70% salt and 30% calcium chloride) (Cho 2003). The pre-wetted

Table 1 Status of the pilot bridge: 'J' bridge.

Route	Bridge name	Super-structure	Completion year	Location	Length (m)	Number of lanes	Year of investigation	Direction
Yeongdong	J	PSCB	1998	Pyeongchang	150	2	2007	Gang-neung bound

PSCB pre-stressed concrete box girder.

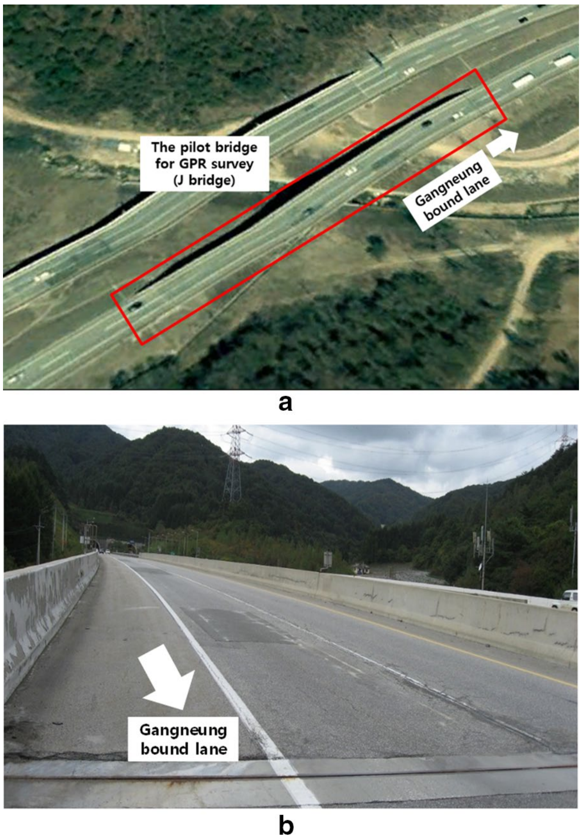

Fig. 2 Photos of the pilot bridge ('J' bridge); **a** aerial plan view of the pilot bridge obtained from Google maps (an image taken on April 23, 2005), **b** overall view showing the surface condition (patching, cracking, efflorescence, etc.) of the pilot bridge taken on the Gangneung bound lane (an image taken on the survey day).

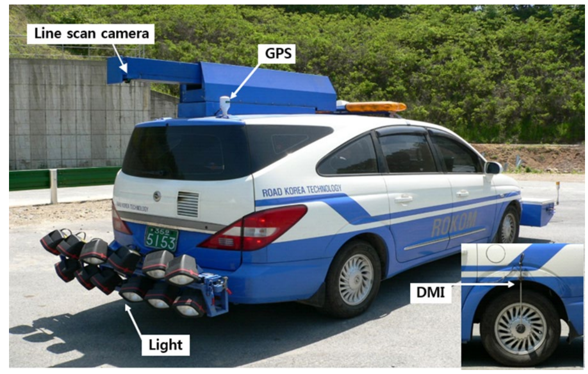

Fig. 3 Photo of the road surface imaging system used for continuous surface image acquisition on the pilot bridge.

salt spreading method has demonstrated to significantly improve the workability of the spraying process and the effectiveness of the deicing agents due to the wet salt that clings to the road. However, some researchers have reported that this method could exacerbate the chloride-induced deterioration in concrete and create a corrosive environment of rebars in concrete. This is mainly due to two reasons: (1) the pre-wet deicing materials can penetrate the concrete more easily than the solid materials; and (2) the improved workability of the spraying process leads to more deicing chlorides on the roadway.

3.2 Surface Visual Inspection

A road surface imaging equipment was used to perform a visual inspection on the surface of asphalt overlays (Fig. 3). This device includes a combination of multiple sensors: a line scan high-resolution camera at the rear top of the vehicle for the surface image acquisition, a GPS system, and a distance measuring instrument (DMI) for automated location measurements. This equipment was driven at an average speed of 80 km/h to collect the images of the road surface of all lanes that includes the shoulders. The location and areal extension of deteriorations from various sources were calculated by using an image-processing computer program.

Figure 4 shows the surface condition map of asphalt concrete based on the stitched photos generated from the computer program. Table 2 summarizes the evaluation results of the condition in the pilot bridge based on the visual inspection according to the guidelines of MLIT and KISTEC (2003). The total deteriorated areas in the pilot bridge were calculated to be 385 m^2. Over 25% of all surveyed areas (1530 m^2) has a condition that requires immediate repair due to attaining a grade of 'e'.

3.3 Detailed Survey from Core Samples

Thirteen core samples were extracted at the shoulder where severely damaged regions were expected. The extracted core samples include pavement layer, waterproof layer, and part of the concrete bridge deck. The core hole was restored by filling it with a rapid setting cement. The core samples were washed with clean water to remove debris and dust on the surface before visual inspection using a high-resolution camera (Fig. 5). A small amount of water was dropped to evaluate the performance of the waterproof layer. In this study, the deteriorated depth was defined as the depth from the top surface of the concrete layer to the surface of the undamaged concrete after removing any damaged part of the concrete (i.e., decomposed concrete elements and/or separated part). First, the depth of a core hole, which is denoted as 'A' in Fig. 6, was measured in the field; the depth of the asphalt overlay and the solid part of the concrete, which are denoted as 'B' and 'C', respectively (see Fig. 6), were measured in the laboratory; and the

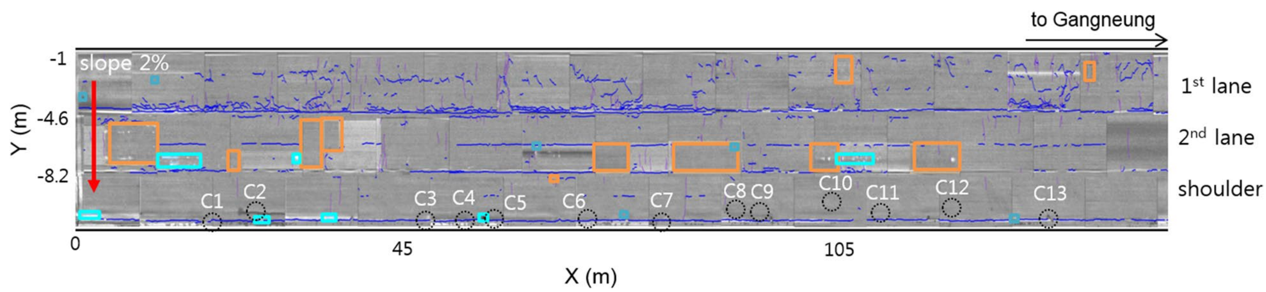

Fig. 4 Surface condition map obtained from the pilot bridge deck, which includes various types of surface damages (◯: core, —: surface-breaking cracks, □: efflorescence, □: patching and □: pothole).

deteriorated depth of concrete, d_{damage}, which is denoted as 'D' in Fig. 6, is calculated as follows,

$$d_{damage} = A - B - C \tag{8}$$

where A, B, and C are the depth of a core hole, the thickness of asphalt overlay and solid part of the concrete, respectively.

Table 3 summarizes the survey results from the detailed visual inspection of the 13 core samples. It was observed that most of the waterproofing layer was either deteriorated, vanished, or was completely lost in most concrete cores. The deteriorated depth of concrete was in the range of 1 to 82 mm. The common types of concrete deterioration were observed to be the decomposition of concrete constituents due to freeze–thaw action on top of the concrete (9 core samples) and delamination in concrete (3 core samples). Based on the survey results of 4 core samples with rebars, the clear covers of rebars were measured between 53 and 73 mm (Fig. 5b). In this study, corrosion of rebars was not observed unless the deterioration depth of concrete exceeded the clear cover of the rebars. Therefore, the concrete deterioration of the pilot bridge in this study was mainly attributed to the freeze–thaw action, with a deterioration mechanism as follows: the rainwater and deicing salt penetrated first the area of the damaged overlay, and then penetrated the concrete further through the weak points with poor waterproofing (Rhee et al. 2018). Subsequently, the freeze–thaw action could enhance the porosity and microcracks through weakening and/or softening the microstructure and through decomposition of the concrete components.

Figure 7 shows the variation of chloride contents of concrete with respect to the depth of core samples C3, C9, and C10. The chloride concentration at the rebar location (50 mm) of C3 and C10 exceeded 1.2 kg/m^3. This is a critical value of triggering corrosion of rebars in concrete described in the guidelines (MLIT and KISTEC 2003). Particularly, C10 exhibited a relatively high chloride content of 2.8 kg/m^3 at the surface of the core sample (about 80 mm from the top surface of the concrete layer). It was observed that the rebar in the C10 lost about 40% of the section due to corrosion activities (see Fig. 5). However, the rebar in the C3 did not show any evidence of corrosion. This phenomenon also supports the chloride-induced deterioration (corrosion of rebars) occurrence after the concrete deterioration due to freeze–thaw action in the pilot bridge.

3.4 GPR Survey

GPR survey was conducted by using 4 channel, 1 GHz air-coupled GPR antennas of Geophysical Survey Systems, Inc. (GSSI), which was installed at the rear of a vehicle (Fig. 8). Figure 9 depicts typical GPR B-scan images corresponding to the sections of the bridge decks under 1st, 2nd, and shoulder lanes. Some of the radar waves emitted from the transmitting antenna are reflected at the media interface (air/overlay surface, A/C interface, and the upper surface of rebar), and some penetrated through the media (overlay and concrete) to lose the energy of the radar wave. The received signal is stored for the analysis of the media characteristics and location (depth). The analytic software, RADAN® (GSSI 2009), was provided from the same company.

The GPR signals were acquired with the sampling rate of the GPR data set to 12 scans/m (i.e., 1 scan per every 80 mm) in the longitudinal direction. The vehicle, where the GPR system is mounted, was driven at the investigation speed of 80–100 km/h to avoid disturbing traffic flow. This sampling rate is much lower than the common sampling rate for ground-coupled GPR operated by normal walking speed, about 50–200 scans/m. The low sampling rate for the air-coupled GPR in this study could introduce some errors in the attenuation and relative permittivity measurements. However, higher sampling rate decreases a survey speed, which could result in higher survey costs and more importantly, could increase a risk of a traffic accident on expressway. Based on 20 years of operational experiences in Korea Highway Corporation, a sampling rate for bridge deck survey using air-coupled

Table 2 Summary of visual inspection on the surface of the pilot bridge.

Lane	Types of deterioration										Rating	
	Longitudinal cracks		Transverse cracks		Efflorescence		Patching		Pothole			
	Quantity	Length (m)	Quantity	Length (m)	Quantity	Area (m^2)	Quantity	Area (m^2)	Quantity	Area (m^2)	Damaged ratio (%)	Grade
1st	407	443.6	136	102.9	0	0.0	2	4.8	7	0.4	31.1	e
2nd	179	212.7	65	40.1	16	2.3	10	77.1	7	0.4	28.8	e
Shoulder	79	174.5	21	19.3	4	1.1	1	0.2	7	0.9	13.4	d
Total	665	830.8	222	162.3	20	3.4	13	82.1	21	1.7	25.1	e

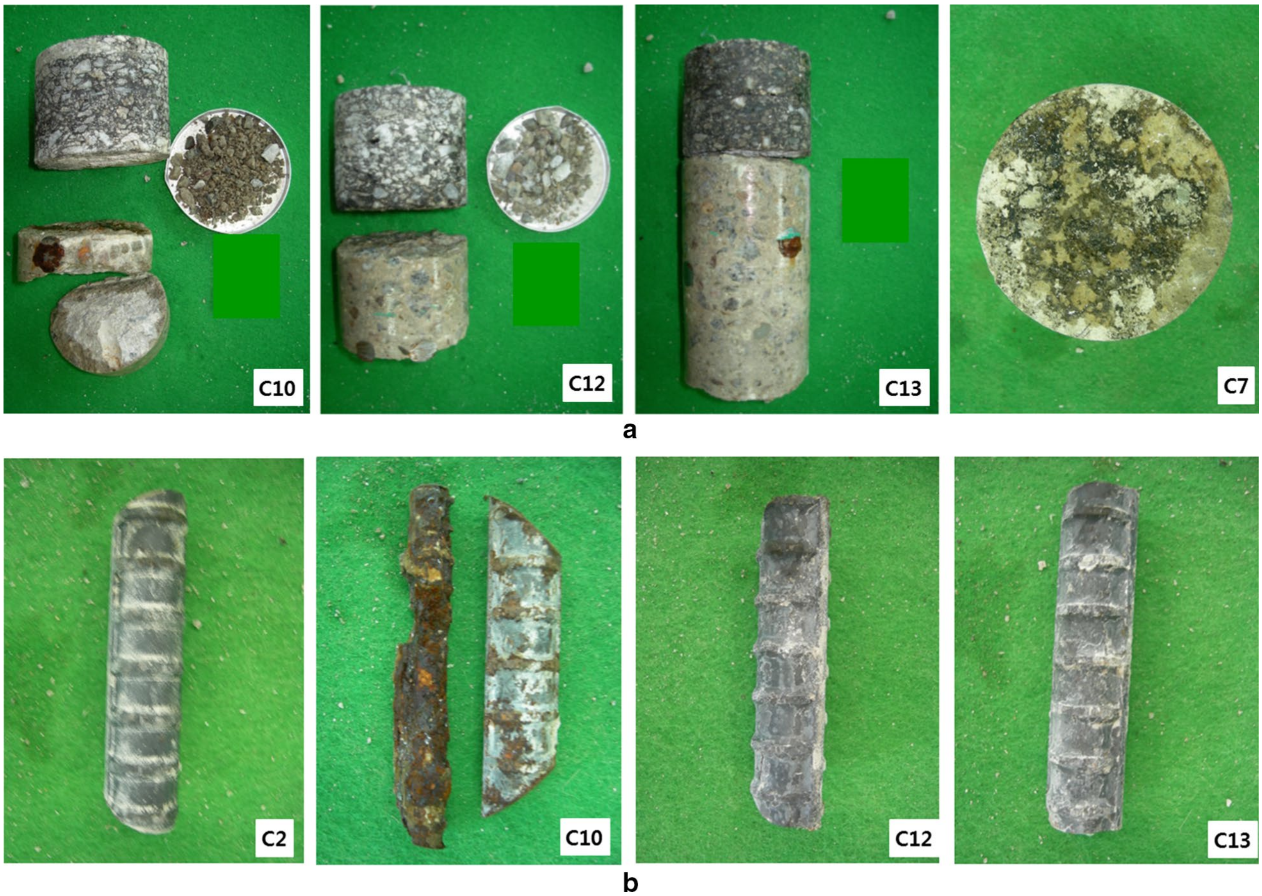

Fig. 5 Visual evaluation of deterioration of concrete and rebar through core samples; **a** major deterioration pattern and **b** rebar condition.

GPR sets between 12 and 14 scans/m depending on the highway speed. It has been observed that the errors are still within a reasonable range for the condition assessment of concrete bridge decks in Korea expressway by a preliminary field survey. A total of 12 lines of GPR scanning (4 channels × 3 lanes) was conducted with a resolution of 500 mm (the center-to-center distance between antennas) in the transverse direction. Consequently, a total of 21,363 scanned data was obtained on the pilot bridge that covers most of the decks, including the shoulder. The longitudinal resolution of 12 scans/m was reasonable considering the actual spacing of rebars in the pilot bridge, 300 mm between transverse rebars in the field and down toward 150 mm near the joints and piers.

In accordance with the field operation protocol in KEC, the GPR survey was conducted at least 24 h after the precipitations. Moreover, the survey was only conducted after confirming that the air-dried surface of an asphalt concrete layer had no standing water on the pavement surface and had no considerable debris that would affect the GPR radar signal interpretations. In terms of the condition assessment of concrete bridge decks with asphalt overlay, it was observed from the field experiences in KEC that the rainy season or the day after rain is the best time for the GPR survey. The basis of the observation can be explained by the rain water remaining in the asphalt-concrete interface. Penetrating water and de-icing material in asphalt and concrete could significantly affect the amplitude of the reflection from the asphalt–concrete interface that increases the relative permittivity of asphalt and concrete. As such, GPR survey of the wet condition identifies 'likely' deteriorated concrete more clearly than in the dry condition (Rhee and Choi 2017). The weather record of the pilot bridge location for 30 days prior to the survey exhibited humid and frequent rainy days. The temperature prior to the GPR survey was in the range of 10 °C to 14 °C. Therefore, the water in asphalt and concrete pore systems are not frozen, which indicates a suitable survey condition (Table 4).

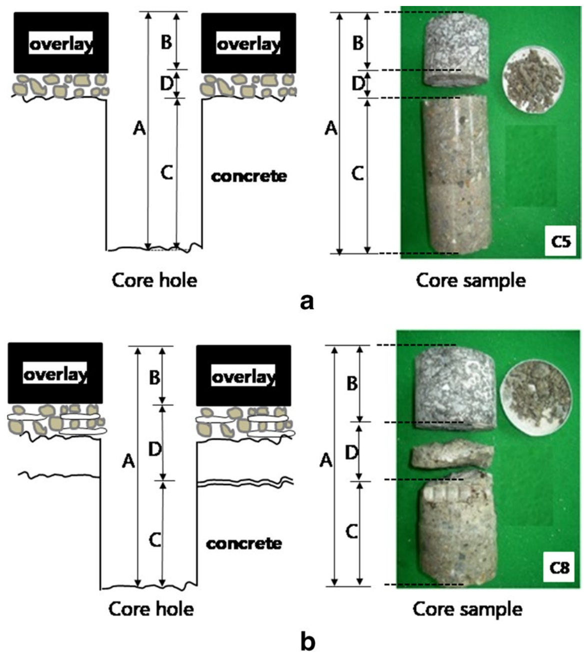

Fig. 6 Illustration of criteria in the estimation of the deteriorated depth from core samples with: **a** scaling and decomposition of concrete constituents, and **b** with delamination.

4 Results and Discussion

4.1 Relative Permittivity of Concrete

Figure 10 shows the distribution of relative permittivity at the interface of the bottom surface of asphalt overlays and the top surface of concrete bridge deck (A/C interface). The average relative permittivity was determined to be 11.7 with a standard deviation of 2.7, which surpasses the relative permittivity of sound concrete that is within the range of 5 to 10 (ASTM D6432 2011). Overall, the high value of relative permittivity is mainly attributed to the presence of water at A/C interface caused by damages in asphalt concrete layers, poor waterproofing, and material deterioration. Areas with high relative permittivity value were determined to occur around the wheel paths, which coincide with the intensive surface-breaking cracks (Fig. 4). Furthermore, large values of relative permittivity were observed around $X = 70–120$ m on the 2nd traffic lane, which corresponds to the location of pavement patches. Results indicate that the deterioration in bridge decks could still occur even after repair due to the presence of weak points. In addition, the area around the barrier on the shoulder has a high relative permittivity due to the penetration of rainwater.

Figure 11 shows the variation of the relative permittivity measured near A/C interface ($\varepsilon_{A/C}$) where the deteriorated depth of concrete bridge deck was measured from core samples (d_{conc_damage}). The relationship between $\varepsilon_{A/C}$ and d_{conc_damage} is established by a linear regression analysis that is given in Eq. (9):

$$\varepsilon_{A/C} = 0.056\, d_{conc\_damage} + 11.14 \quad (9)$$

The coefficient of determination (R^2) was calculated to be 0.55. According to the statistical hypothesis test

Table 3 Summary of core survey.

ID	Core location		Pavement thickness (mm)		Waterproof layer		Rebar cover thickness (mm)		Rebar condition	Concrete deteriorated depth (mm)	Concrete condition
	X (m)	*Y* (m)	$H_{asp,core}$	$H_{asp,GPR}$	Bonding	Performance	$H_{CC,core}$	$H_{CC,GPR}$			
C1	19	− 10.4	72	90	D	Loss				5	DC
C2	25	− 9.6	87	100	D	Loss	73	70	Clear	30	DC
C3	47.9	− 10.5	91	95	D	Loss				40	DC + DL
C4	52.7	− 10.4	94	95	D	Loss				55	DC + DL
C5	57.6	− 10.5	81	90	D	Loss				35	DC
C6	70	− 10.2	84	90	D	Loss				14	Other
C7	81	− 10.4	79	85	D	Poor				1	SC
C8	91	− 9.6	73	85	D	Loss				42	DC + DL
C9	94	− 9.8	82	85	D	Loss				35	DC
C10	103	− 9.3	80	90	D	Loss	72	80	Section loss	82	DC + DL
C11	110.1	− 9.8	82	90	D	Poor				3	SC
C12	119.6	− 9.5	79	85	D	Loss	70	60	Clear	30	DC
C13	133	− 10.2	75	80	D	Loss	53	80	Clear	6	SC

$H_{asp,core}$ and $H_{asp,GPR}$ are the thickness of asphalt overlay (pavement) measured from core samples and GPR survey, respectively.

$H_{cc,core}$ and $H_{cc,GPR}$ are the thicknesses of clear cover of top reinforcing bars measured from core samples and GPR survey, respectively.

D de-bonding, *DC* decomposition of concrete constituents, *SC* scaling, *DL* delamination.

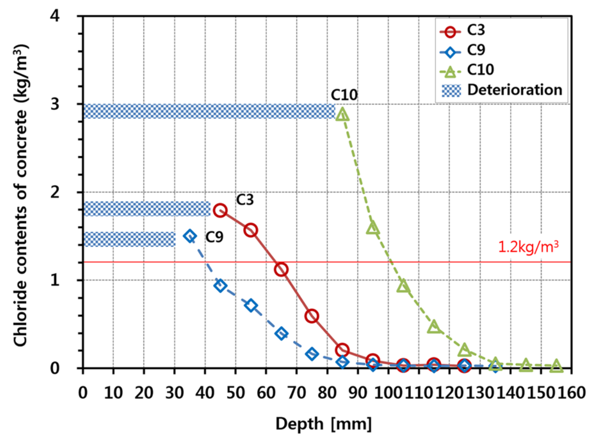

Fig. 7 Analysis result of chloride contents of concrete by depth.

Fig. 8 Photo of air-coupled GPR system used for concrete bridge deck survey in this study.

using the *t*-test and null hypothesis, the relationship, which was obtained by chance, is rejected at a statistical significance level of 0.01 (McCall 2000). Therefore, the relationship between $\varepsilon_{A/C}$ and d_{conc_damage} is statistically significant at 99% confidence level. It can be observed that concrete with a higher degree of deterioration is more permeable due to increased porosity and microcracks that would have higher water capacity, which results in greater relative permittivity. It is not certain if the simple equation is effective for accurate estimation of the depth of deteriorated concrete from the relative permittivity value because of relatively large mean average error (MAE) between the estimated and measured depth of deteriorated concrete (MAE of 13.63 mm). However, the experimental relationship in this study is still valid to demonstrate the relative permittivity values near the A/C interfaces, which is informative of the severity of concrete deterioration in the bridge deck with asphalt overlay.

Based on the survey, the present work proposes that the relative permittivity should not be less than 11 to avoid failure of the waterproof layer, which may lead to surface deterioration of the concrete. The relationship illustrated in Eq. (9) was derived from the observation of the pilot bridge under wet condition where the A/C interface and concrete bridge deck contain a sufficient quantity of water. The GPR survey performed under various time and weather condition (Rhee and Choi 2017) may result in different distribution of relative permittivity, which may affect the relationship between $\varepsilon_{A/C}$ and d_{conc_damage}. Thus, it is necessary to better understand the variation of relative permittivity, which depends on the absorptive capacity and water content of various concrete bridge decks in Korea expressway networks.

4.2 Depth-Corrected Attenuation

Figure 12a shows the maps of the depth-corrected attenuation $\delta_{cover\_conductive}$ of GPR reflected signals from the top rebars in concrete. The $\delta_{cover\_conductive}$ was calculated using Eqs. (5), (6) and (7). For comparison purposes, the maps representing the distribution of the total attenuation at the top layer of rebars (δ_{rebar}) and attenuation through the pavement layers ($\delta_{overlay}$) are illustrated in Figs. 12b and 12c, respectively.

It is important to calibrate the effect of concrete cover of actual rebars on the GPR attenuation in order to accurately estimate $\delta_{cover\_conductive}$. Figure 13a shows the variation of $\delta_{cover}\left(\delta_{cover\_depth} + \delta_{cover\_conductive}\right)$ with respect to two-way-travel time (TWTT) of GPR signals reflected through concrete cover of the top rebars. The data points were extracted from twelve B-scan images (Fig. 9). To estimate the reference attenuation curve that represents sound concrete, the following assumptions are made: at least some parts of the deck areas in the test bridge remain in sound condition and the attenuation of GPR signals derived from concrete cover in sound condition is linearly proportional to TWTT. The attenuation curve of the solid concrete was determined based on a linear regression analysis of the 90th percentage of attenuation data from the concrete cover in this study (refer to the red line in Fig. 13a). Moreover, the slope in δ_{cover} and TWTT is derived from the actual variation of rebars in the pilot bridge. Subsequently, Fig. 13b shows the depth-corrected attenuation by subtracting the contribution of the geometric damping. The thickness of the asphalt overlay and clear cover of rebars that was measured by GPR was compared with the measured values derived from the core samples (Table 3). As for the overlay

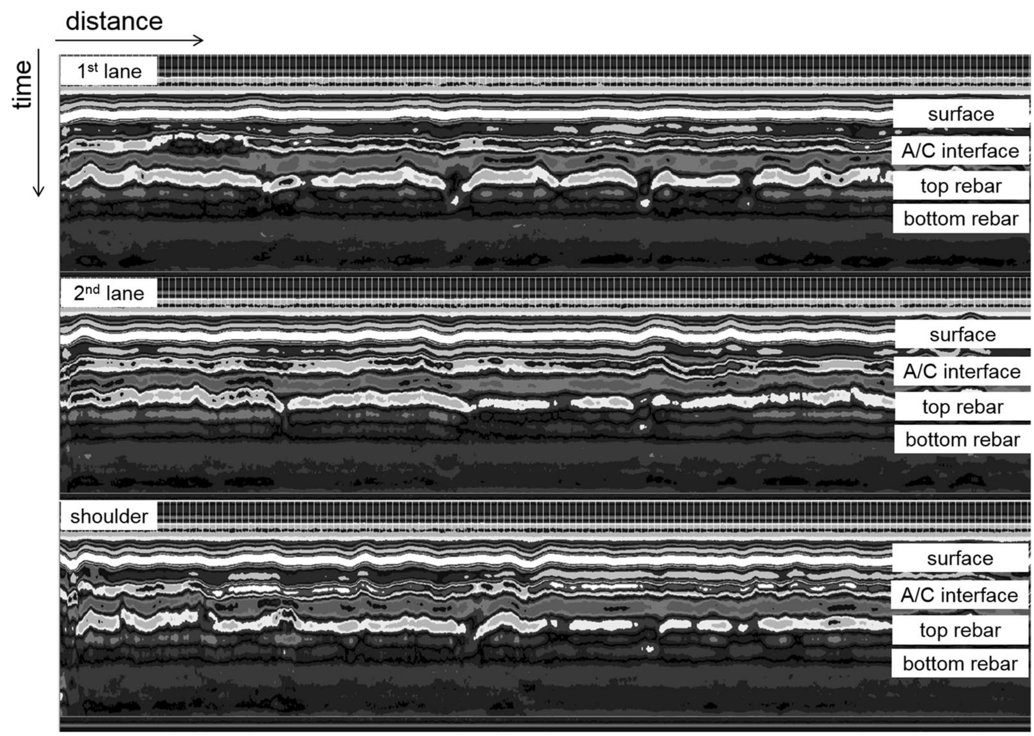

Fig. 9 Typical GPR B-scan images measured by air-coupled GPR system on the pilot bridge.

Table 4 Weather condition of the location of the pilot bridge for 30 days.

Survey date	R.H of air	Weather	Remarks
October 11, 2007	76%	Haze	Daily temperature: average 7.9–23.7 °C, highest 13.9–27.5 °C, lowest 1.4–20.0 °C Rainfall: 0–75.5 mm Weather: rainy 24 days[a], haze 30 days

Weather data from Korea Meteorological Administration (KMA) for 30 days prior to the survey date (September 12, 2007–October 10, 2007).

[a] Including rain-sensing days.

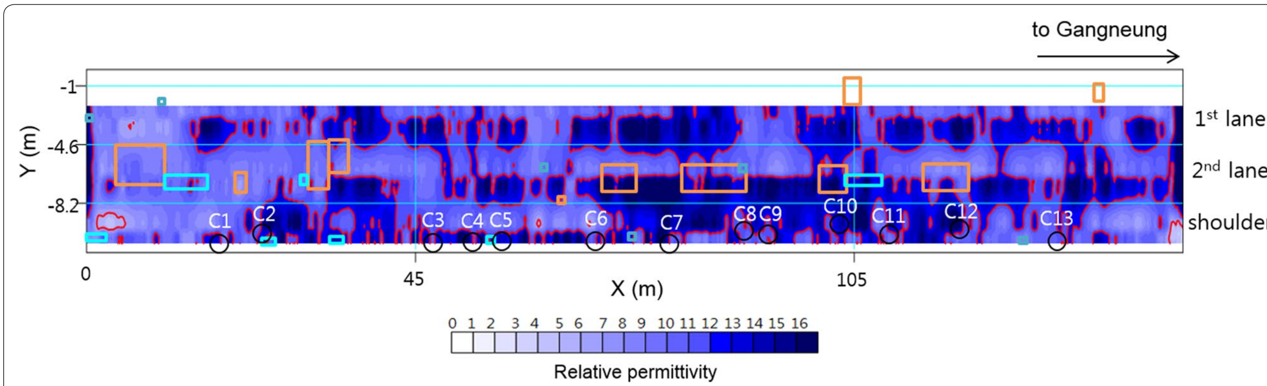

Fig. 10 Condition map based on the relative permittivity of concrete measured by air-coupled GPR system on the pilot bridge: red lines indicates the relative permittivity values of 6 and 12. For a comparison, various types of damages on the surface in Fig. 5 are shown in the figure (◯: core, —: surface-breaking cracks, □: efflorescence, □: patching and □: pothole).

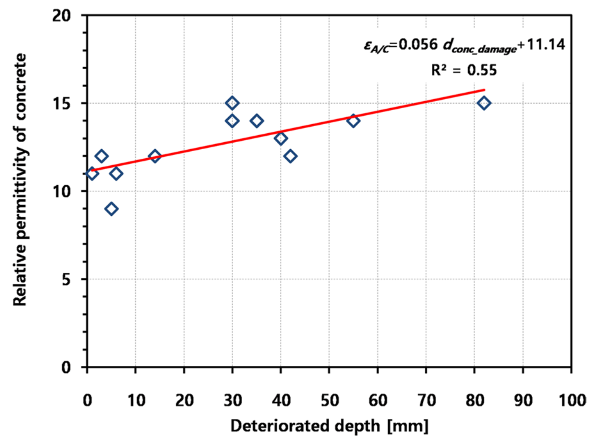

Fig. 11 Relationship between relative permittivity of concrete measured by air-coupled GPR system on the pilot bridge and deteriorated depth measured from core samples.

thickness, the errors between the predicted and measured thickness are within the range of 1% to 18% with an average of 7.8% while the range of error values for cover thickness is between 3 and 27% with an average of 12.5%. The errors are attributed to the experimental variations of the EM properties of actual materials (asphalt overlay, waterproof layer, concrete) that were not considered in the GPR field survey. However, the errors are still within the acceptable range of values in the field survey.

Figure 14 shows the variation of the depth-corrected attenuation, $\delta_{cover\_conductive}$, from the GPR survey with the deteriorated depth of concrete bridge deck measured from core samples (d_{conc_damage}). An approximate equation representing the relationship between $\delta_{cover\_conductive}$ and d_{conc_damage} is established by a linear regression analysis as follow:

$$\delta_{cover\_conductive} = 0.076\ d_{conc\_damage} + \ 4.71 \tag{10}$$

The measured value of the coefficient of determination (R^2) is 0.53. Similar to the relative permittivity, the relationship was confirmed to be statistically significant at 99% confidence level based on the results of the *t*-test (McCall 2000). Higher concentration of chloride ions and water could lead to a more severe deterioration of the concrete in depth and higher attenuation of GPR signals reflected from the rebars. Like relative permittivity, the equation may not be effective to accurately estimate the deteriorated depth in concrete due to relatively large errors (MAE = 13.09 mm). Nevertheless, it is still reasonable to say that $\delta_{cover\_conductive}$ is a useful indicator of the degree of concrete deterioration in the bridge deck with asphalt overlay.

For practical applications, the study proposes two critical values to accurately interpret the depth-corrected attenuation values from the GPR survey. The first criterion is the value of $\delta_{cover\_conductive}$, which should not be less than 5 dB and could determine the presence of concrete deterioration on the top of concrete. The second criterion is $\delta_{cover\_conductive}$, where the value should not be less than 11 dB in order to determine the degree of the corrosive environment around the rebars in concrete. However, the criteria in practice should be carefully utilized since the depth-corrected attenuation of GPR signals could be affected by many factors such as types of GPR equipment, water content of bridges, severity and types of deterioration in concrete, thickness and condition of asphalt overlay, and procedure of the depth-correction. Therefore, it is difficult to generalize the relationship between $\delta_{cover\_conductive}$ and d_{conc_damage}. However, the experimental results are useful to better understand the relationship between $\delta_{cover\_conductive}$ and d_{conc_damage} through the GPR field survey. This, in turn, could further improve the reliability of GPR technologies for the condition assessment of actual concrete bridge decks with asphalt overlay on Korea expressways.

4.3 Proposal of a Dual-Criteria Based on the GPR Signal Interpretation

Figure 15 illustrates the relationship of the depth-corrected attenuation of concrete cover against the relative permittivity of concrete on the top surface of the bridge decks. Overall, the depth-corrected attenuation tends to increase as the relative permittivity of concrete increases. However, numerous data points are far from the best-fit line of the two GPR parameters, which is shown as a red solid line in Fig. 15. This deviation is due to the two GPR parameters that are based on different fundamental principles, physical significance, and properties (Table 5). Relative permittivity is computed by the amplitude of the received EM wave reflected from the interface of a medium. The EM wave is emitted and is mainly a factor to indicate the water content ratio at the concrete surface in a bridge deck (A/C interface). On the other hand, the depth-corrected attenuation is computed by excluding the attenuation due to distance (geometric and dielectric loss) from the attenuation (loss) of the EM wave transmitted to a medium. This is a factor to evaluate the conductivity of the chloride ion in the concrete cover. It has been demonstrated from the 20 years experience of GPR field applications in KEC that the single-parameter-based (the relative permittivity or depth corrected attenuation) GPR survey is not enough to evaluate the deteriorated depth of concrete on the basis of accuracy.

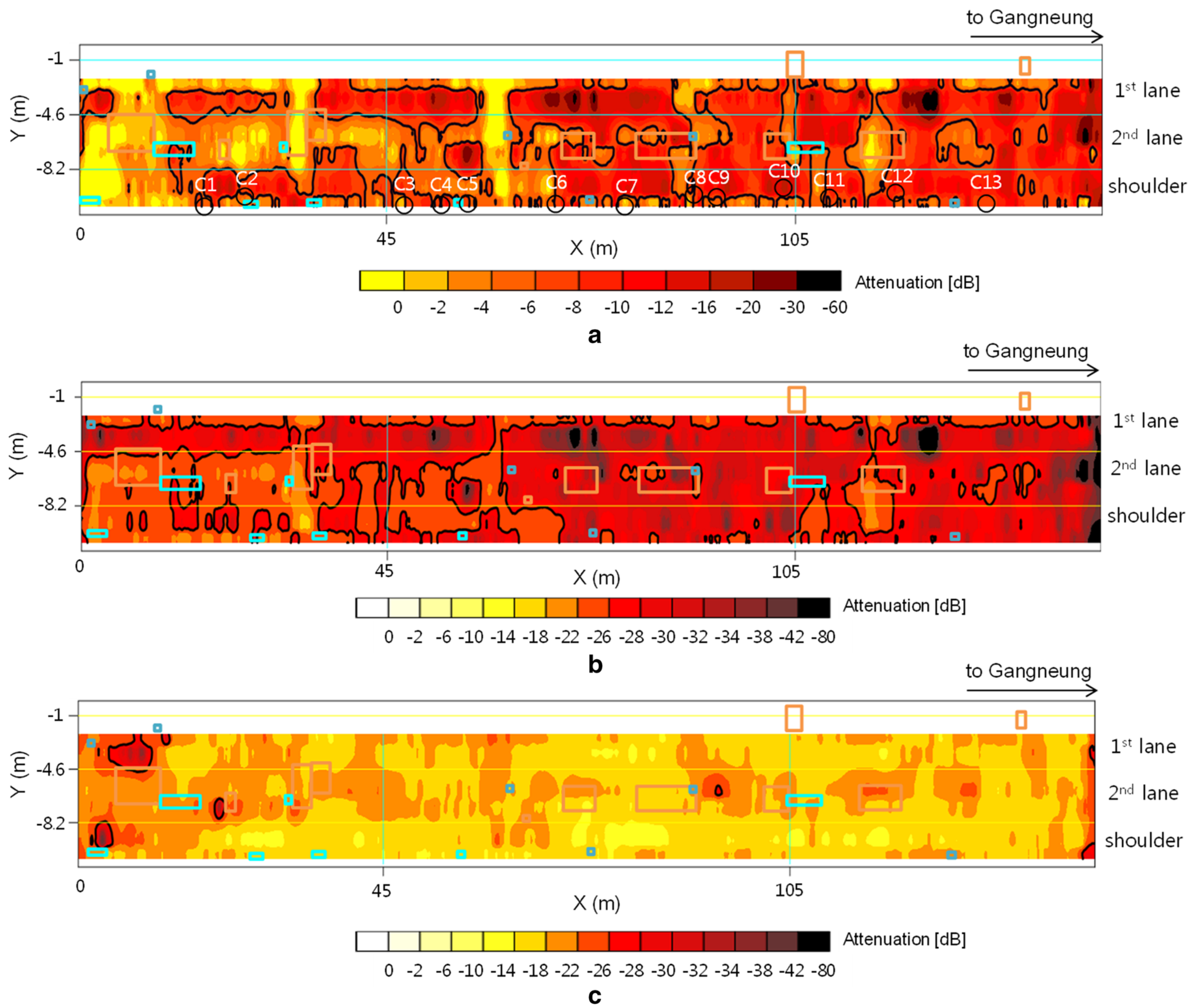

Fig. 12 Condition map based on the attenuation of EM waves measured by air-coupled GPR system on the pilot bridge: **a** depth-corrected attenuation of concrete cover (black lines indicating − 6 dB), **b** total attenuation at top rebar (black lines indicating − 26 dB) and **c** attenuation of pavement layer (black line − 26 dB). For a comparison, various types of damages on the surface in Fig. 5 are shown in the figure (◯: core, —: surface-breaking cracks, □: efflorescence, □: patching and □: pothole).

The new data interpretation method proposed in this study considers the advantages of GPR analysis to simultaneously apply the relative permittivity of a concrete, ε, and depth-corrected attenuation of concrete cover, δ. Table 6 summarizes the dual-criteria-based evaluation method for condition assessment of concrete bridge decks with asphalt overlays in the Korea expressways.

Figure 16 shows the condition map of deterioration prediction in consideration of both relative permittivity of concrete and depth-corrected attenuation at top rebar. The images of the internal concrete of the bridge deck investigated during the repairing work are in line with the five categories of deterioration listed in Table 6. Examining this in conjunction with the previous pilot bridge deck survey result (Fig. 4), 'Fair' area of poor waterproofing was observed. This area is located around the barrier on the shoulder, where the gathered rainwater was due to the overlay damages (cracking, patching, etc.) and lateral slope. This has led into a 'Poor' stage, at which the early deterioration of concrete started due to the accumulation of chloride ion in concrete. Afterwards, if the deterioration of concrete

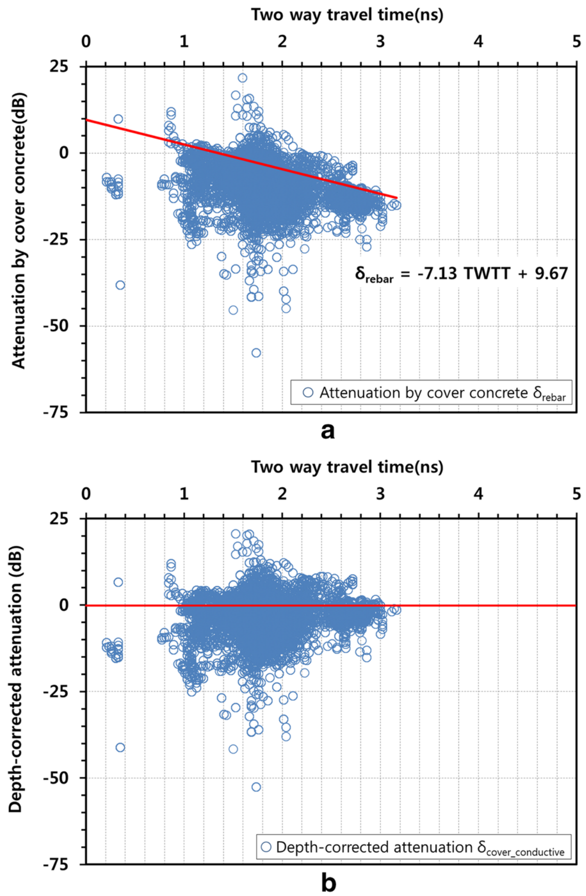

Fig. 13 The variation of attenuation of GPR reflected signal from rebars with TWTT: **a** before and **b** after the depth-correction procedure.

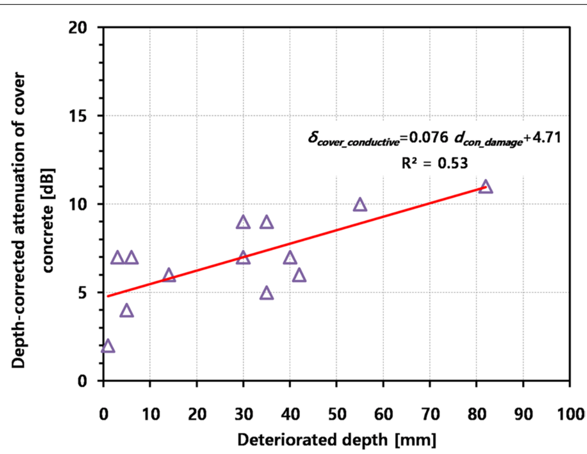

Fig. 14 Relationship between the depth-corrected attenuation measured by air-coupled GPR system on the pilot bridge and deteriorated depth measured from core samples.

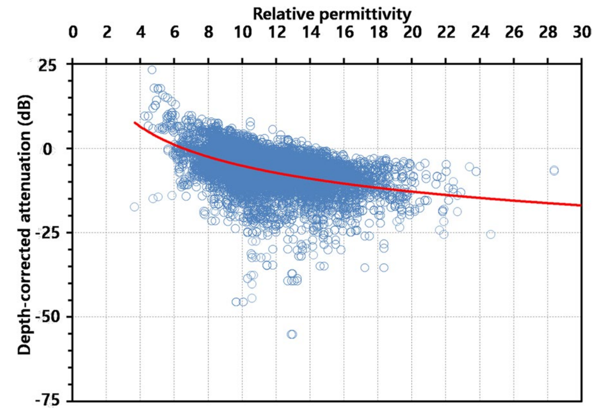

Fig. 15 Relationship between the depth-corrected attenuation of concrete cover and the relative permittivity of concrete on the top surface of the bridge decks.

worsens to reach the location of the rebar, this would then be a 'Serious' stage in which the possibility of corrosion of the rebar is high. The 'Serious' area was observed at wheel path, around the barrier, and around the end of the bridge.

The method of this study is proposed through the understanding of the results of the Korean expressway survey as well as the case study of a particular bridge currently under public service. A generalization of the result of this study would still require a systematic test of data.

5 Summary and Conclusions

This study proposed an advanced analysis method of evaluating the depth of deteriorated concrete in concrete bridge decks with asphalt concrete using air-coupled GPR system. The method was applied to a pilot bridge, selected from the Korea expressway network, to analyze the validity of the proposed analysis technique with GPR. The conclusions derived from this study can be summarized as follows.

1. It was observed that the pilot bridge, located in the coldest and snowiest region in Korea, was mainly deteriorated by the freeze-and-thaw action. A detailed visual inspection of the 13 core samples revealed that the main types of concrete deterioration include the decomposition of concrete constituents due to freeze–thaw action on the top part of the concrete and the delamination in concrete. Corrosion of reinforcing bars (rebars) was not observed

Table 5 Comparison of the two GPR parameters (relative permittivity and depth-corrected attenuation of concrete cover) for the condition assessment of concrete bridge decks with asphalt overlays.

Classification	Relative permittivity	Depth-corrected attenuation
Principle	Computed with the amplitude of received EM wave as reflected from the interface of a medium to which an EM wave is emitted	Computed by excluding the attenuation due to distance (geometric and dielectric loss) from the loss (attenuation) of the EM wave transmitted to a medium
Physical significance	Relative permittivity at A/C interface (Relative permittivity at top concrete of bridge decks)	Evaluation of the attenuation by conductivity of the chloride ion in concrete cover
Advantages	Evaluates waterproofing at A/C interface (water contents ratio of concrete) Correlated to deteriorated depth (poor waterproofing)	Assess the corrosion environment of rebar due to chlorides penetration Correlated to deteriorated depth (deicer usage condition)
Limitations	Difficult to assess the deteriorated depth if the concrete bridge deck is not in hydrated state	Need for the consideration of pavement layer condition (thickness and deteriorated or not) Need for the establishment of a standard method of depth correction
Deterioration evaluation	Assessment of soundness of the waterproofing at A/C interface	Evaluation of corrosion environment of rebar and deteriorated depth of concrete

Table 6 Dual-criteria based GPR interpretation for condition assessment of concrete bridge decks with asphalt overlays in Korea expressway networks.

Category	GPR		Assessment and analysis			
	Relative permittivity	Depth-corrected attenuation (dB)	Waterproof function	Deteriorated environment	Concrete deterioration	Rebar corrosion
Good	$\varepsilon < 11$	$\delta < 5$	Good	×	×	×
Fair	$\varepsilon \geq 11$	$\delta < 5$	Poor	×	×	×
Poor	$\varepsilon \geq 11$	$9 > \delta \geq 5$	Good	○	○	×
Serious	$\varepsilon \geq 11$	$\delta \geq 9$	Poor	○	○	○
Watch	$\varepsilon < 11$	$\delta \geq 5$	Good	○	○	Δ

×: low possibility of damage, Δ: unknown, ○: high possibility of damage.

unless the deteriorated depth of concrete exceeded the clear cover of the rebars.

2. Relative permittivity was measured on the top surface of the concrete layer [asphalt-and-concrete (AC) interface] in the pilot bridge. Generally, the large relative permittivity manifested in some areas is mainly attributed to the presence of water near the AC interface. Furthermore, it was determined that the relative permittivity values near the A/C interfaces are informative of the depth of concrete deterioration. This study proposed that the relative permittivity of concrete be no less than 11 as a criterion to determine the failure of the waterproof layer. This may cause a deterioration in the surface of concrete in the concrete bridge decks with an asphalt overlay.
3. It was demonstrated that the depth-corrected attenuation of GPR reflection signals from the rebars in the concrete is a useful indicator of estimating the degree of concrete deterioration in the bridge deck with asphalt overlay. For the practical applications, this study proposes two critical values of the depth-corrected attenuation: $\delta_{cover\_conductive} \geq 5$ dB as a criterion to determine the presence of concrete deterioration on top of the concrete; and $\delta_{cover\_conductive} \geq 11$ dB to determine the degree of the corrosive environment around the rebars in concrete.
4. A new standard based on the dual-criteria of the GPR interpretation method was proposed to improve the limitations of GPR analysis based on the individual factors of relative permittivity and depth-corrected attenuation. The test areas are subdivided into five categories, 'Good', 'Fair', 'Poor', 'Serious,' and 'Watch'. The validity of the method was verified by a comparison with the actual concrete condition of bridge deck investigated during the repairing works. The proposed standard is effective for better estimating

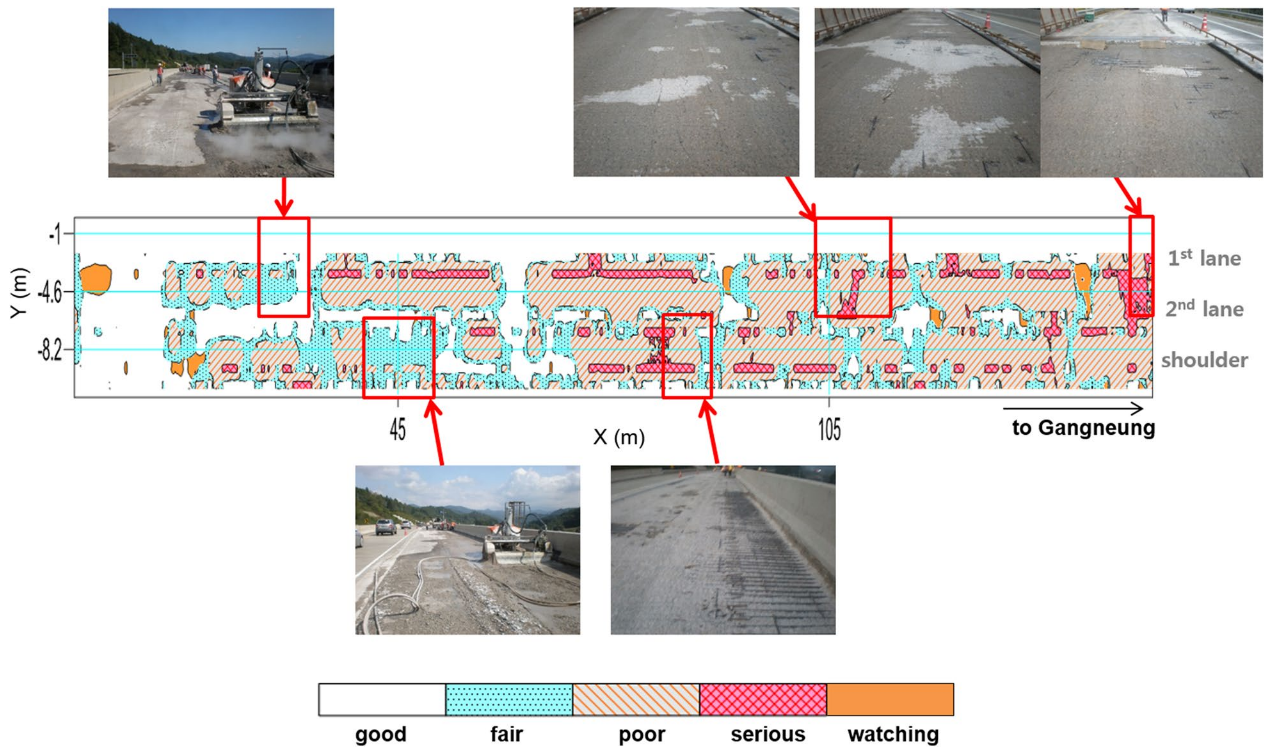

Fig. 16 Condition map based on both relative permittivity of concrete and depth-corrected attenuation at top rebar with images of the internal concrete of bridge deck during repairing work.

the internal concrete condition in the concrete bridge deck with asphalt overlay.

5. Nonetheless, the method of this study is proposed through the understanding from the results of the Korean expressway survey as well as the case study of one bridge, selected from the Korea expressway network, that is currently under public service. Data from other bridges are needed to calibrate the model and to establish the probability relationship between the depth of deterioration in concrete bridge decks and the GPR parameters.

Authors' contributions
JR conducted the GPR measurements, processed the experimental data, and performed the analysis. JR and JC supervised the project. JR and SK conceived the dual-criteria based GPR interpretation algorithm, drafted the manuscript and designed the figures. All authors discussed the results and contributed to the final version of the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The experimental data used to support the findings of this study are included in the article.

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