

Article

Research on the Quality of Asphalt Pavement Construction Based on Nondestructive Testing Technology

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Abstract: In order to better evaluate the construction quality of asphalt pavement, nondestructive testing techniques are used to inspect newly paved asphalt mixture pavement. The proposed system for the evaluation of asphalt pavement construction quality uses three-dimensional ground-penetrating radar (GPR) and a non-nuclear density gauge. The GPR and the non-nuclear density gauge test results were used to establish a dielectric constant–porosity model by fitting. This approach can more accurately determine the dielectric constant selection scheme of the GPR based on the average value of every 10 dielectric constant data points in the length direction of the radar antenna and every three data channels in the width direction. The GPR collected the dielectric constants of the road surface based on the total reflection method and used the average value of the local dielectric constant to evaluate the construction quality of the road. The non-nuclear density gauge used the local porosity to assess the construction quality of the road. It is recommended that the two testing schemes described above be used to evaluate the quality of asphalt pavement construction. They can provide theoretical guidance for future applications in practical processes.

Keywords: nondestructive testing; construction quality evaluation system; dielectric constant–porosity prediction model; average of local dielectric constants; proportion of local severe segregation



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1. Introduction

By the end of 2020, China had 160,000 km of motorways open to traffic, putting it in first place globally; the highway coverage of cities with a population of 200,000 or more exceeded 98% [1]. For highways with design lives of 20 years, asphalt mixture pavements are used, but they are susceptible to heavy loads, high temperatures, rain, and other adverse coupled factors [2]. Furthermore, they are prone to early severe damage, such as wheel ruts, potholes, looseness, flooding oil, and swelling within the first 1–2 years of use [3]. As these phenomena are not evident early on in use, the development of early failure is difficult to control, increasing the maintenance and repair costs of the road at later stages, affecting the comfort and safety of vehicle travel, and reducing the normal service life of the road. The quality control problems contribute to early failure during the construction of new asphalt mixture pavement [4], which is mainly reflected by the porosity of the asphalt mixture. Thus, the porosity of the asphalt mixture should be controlled to within a reasonable range. Excessive porosity in asphalt pavement can cause water and air to enter the pavement, leading to water damage, aging, spalling, and cracking [5]. Therefore, accurate and efficient assessment of the quality of asphalt pavement construction is one of the most important means of preventing the development of early asphalt pavement distress.

Current three-dimensional ground-penetrating radar technology is relatively mature for detecting road thickness [6,7], and electromagnetic pulses are mainly transmitted

through an antenna to penetrate the road surface. The reflected echoes generated by the surface and internal unevenness of the road surface are recorded to measure the penetration depth [8]. Baltruaitis et al. used an existing mathematical model to determine the density of asphalt pavement by drilling a core and using ground-penetrating radar (GPR) [9]. However, the construction quality evaluation system for asphalt mixtures using GPR is still in the developmental research stage [10,11]. Related research has shown that GPR can optimize asphalt pavement design and identify the exact location of internal damage to the pavement [6]. Zhang et al. used GPR to accurately locate and detect wet damage on asphalt pavement, proving that GPR has excellent detection performance [12]. Ma et al. found that GPR is more effective at detecting stripping damage on flexible pavement. In order to achieve this goal, a finite-difference time-domain simulation program was used to study the propagation of GPR signals in a stripped pavement [13]. Although the traditional core drilling and sampling method can accurately measure the density of the structural layer of asphalt pavement [14,15], it is destructive to the pavement, as well as complex and inefficient [15–17]. A non-nuclear density gauge can accurately measure the density of asphalt pavement and other indicators through calibration before the measurement [18]. Wim et al. studied the parameters of the non-nuclear density gauge, and the use of PQI is recommended as part of the standard quality control process by Flanders [19], but this required a single point of detection, which was inefficient [20]. Both existing nondestructive testing methods are under-representative and so cannot accurately and efficiently evaluate the quality of asphalt pavement construction [21]. Therefore, it is necessary to evaluate the construction quality of asphalt pavement comprehensively to improve the construction process of asphalt mixtures and reduce the influence of porosity on the service life of asphalt pavement.

The purpose of this research was to combine three-dimensional GPR with a non-nuclear density gauge. Based on two nondestructive testing techniques, two concepts, the average of local dielectric constant values and the proportion of local porosity, are proposed to establish an asphalt pavement construction quality evaluation system to provide a theoretical basis for later application and development in actual projects.

2. Nondestructive Testing Equipment and Principles

2.1. Three-Dimensional Ground-Penetrating Radar (GPR)

In this test, the Geo Scope^{MK} IV GPR system produced by 3D-Radar was used to study the dielectric constant of asphalt pavement. The system was equipped with a DX1821 air-coupled antenna, distance measuring wheel (DMI), computer, and Geo Scope radar mainframe, as shown in Figure 1. The vehicle-mounted radar system could obtain dielectric constant gray images to reflect the condition of the road in real time. According to the different reflection effects of high-frequency electromagnetic waves in mixtures of different media [22], GPR transmits pulsed high-frequency electromagnetic waves to the asphalt pavement via a butterfly monopole antenna. The reflected electromagnetic wave signals are processed by software to understand the reflection of different media in the pavement's structural layer and obtain the dielectric constant of the road section.

2.2. Non-Nuclear Density Gauge

A new generation of non-nuclear density gauge (PQI 380) from Trans Tech, Adamstown, MD, USA, was used in this study, as shown in Figure 2. Because asphalt mixtures are prepared from asphalt and aggregate, the dielectric constants of these materials vary considerably, and air can be present in the interstitial spaces. The PQI 380 emits a circular electromagnetic wave through the bottom to the asphalt pavement. As the material composition of the mixture changes, the transmission direction and propagation speed of the electromagnetic wave will change accordingly. This causes a difference in the signal received at the receiving end of the instrument, and an empirical algorithm is built into the device for density detection [23]. However, for different types of asphalt mixes with different testing depths, calibration must be carried out before using the PQI 380, as follows.

First, an area of approximately $1.5\text{ m} \times 0.75\text{ m}$ was selected in the calibration area, and three circles were drawn in this area. The PQI 380 measured the density data at each of the five locations of each circle, as shown in Figure 3, then the height and density of five sample cores were measured in the laboratory. The ratio of the actual densities of the core samples to the density measured by the PQI 380 was calculated, and the density correction coefficient was obtained so that the density of the asphalt pavement measured by the PQI 380 at the same location was consistent with the actual density value.



Figure 1. Three-dimensional ground-penetrating radar (GPR) inspection vehicle.



Figure 2. Non-nuclear density gauge (PQI 380).

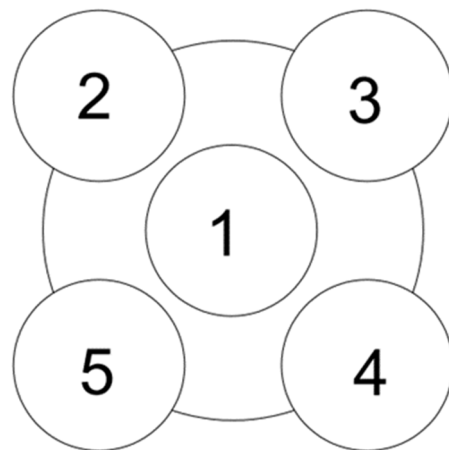


Figure 3. Calibration method of PQI 380.

2.3. Total Reflection Method

The total reflection method was as follows. First, a standard iron plate was placed under the air-coupled antenna, the total reflection signal generated by the GPR electromagnetic wave was collected through the iron plate, and then the electromagnetic wave was transmitted to the asphalt pavement [24,25]. When the electromagnetic wave encountered the layered road surface, a small part was scattered, and a part was received by the receiving antenna. The GPR antenna measured the peak-to-peak amplitude A_0 of the reflection on the road surface and the peak-to-peak amplitude A_p of the reflection from the iron plate, which are defined in Figure 4, and the dielectric constant of the first layer $\epsilon_{r,1}$ was calculated as follows:

$$\epsilon_{r,1} = \left(\frac{1 + \frac{A_0}{A_p}}{1 - \frac{A_0}{A_p}} \right)^2. \quad (1)$$

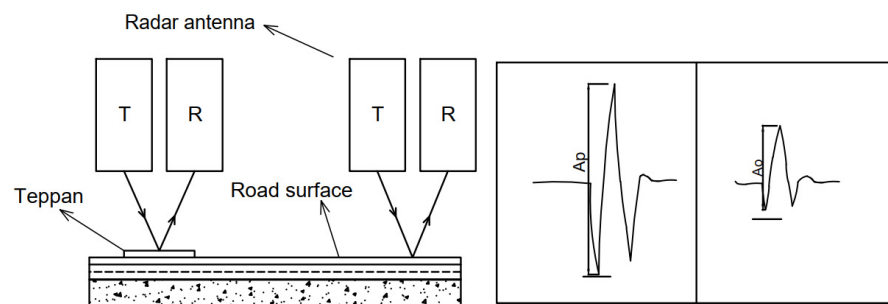


Figure 4. Schematic diagram of total reflection detection method of three-dimensional ground-penetrating radar.

3. Selection of Representative Values for Ground-Penetrating Radar Dielectric Constants

Asphalt mixes are made up of asphalt, aggregate, and filler; the dielectric constant of asphalt is generally in the range of 2.6–2.8, the dielectric constant of aggregate is generally in the range of 4.5–6.4, and the dielectric constant of air is 1. A dielectric constant of the asphalt mixture pavement needs to be assumed to be an overall dielectric constant [26]. The optimal dielectric constant value method can accurately determine the porosity of the pavement, better predict early issues with the road, and enable the asphalt mixture pavement to have a longer service life.

3.1. Design of Scheme for Value of Dielectric Constant for Asphalt Mixture Pavements

The air-coupled antenna used in this study had 21 channels, with 7.5 cm between them, as shown in Figure 5. Each of the 21 channels could collect the corresponding dielectric constants. Therefore, choosing the average value of the appropriate number of channel

data as the representative value of the dielectric constant of the pavement at this time is of great significance for evaluating the construction quality of asphalt pavement. The asphalt layer was examined using 3dr-Examiner data analysis software, and the reflection amplitude of the asphalt layer and the reflection amplitude of the iron plate were obtained. The amplitude total reflection method [25] was used to calculate the dielectric constant of the asphalt pavement and to measure the porosity of the asphalt pavement at this time. By fitting the representative values of the dielectric constant and porosity, a more accurate method of determining the dielectric constant was obtained, and a corresponding dielectric constant–porosity prediction model was established.

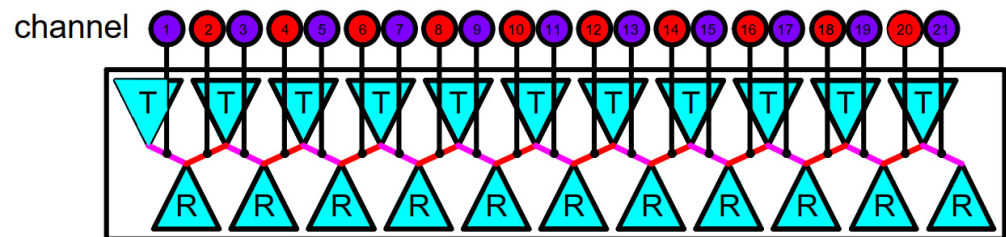


Figure 5. Internal vibrator arrangement of air-coupled antenna of three-dimensional ground-penetrating radar.

In this study, a test Section 5 m in length and 1.5 m in width was designed in the front of the test section, and a grid of squares with an interval of 0.5 m was drawn in the middle section of this road. First, the non-nuclear density gauge was calibrated, and then one data point was collected in an area of $0.5\text{ m} \times 0.5\text{ m}$. Since the acquisition interval in the radar length direction was 0.05 m, every set of 10 data points was averaged in the radar length direction. Three methods for determining the dielectric constant in the radar width direction were examined: Method 1: the dielectric constant of the middle channel of every seven channels in the radar width direction was determined, and a total of 10 data points were averaged; Method 2: the average value of the dielectric constant of the middle three channels of every seven channels was calculated in the radar width direction, and a total of 30 data points were averaged; Method 3: the average value of the dielectric constant for every seven channels was taken in the radar width direction, so a total of 70 data points were averaged, as shown in Figure 6. The dielectric constants measured by the three methods were fitted to the porosity measured by the non-nuclear density gauge to determine which method gave the best fit.

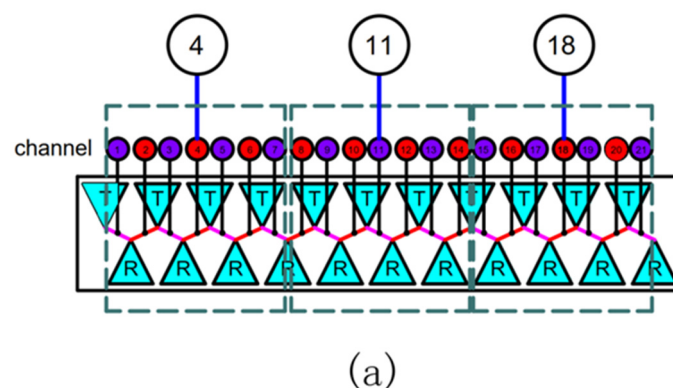


Figure 6. Cont.

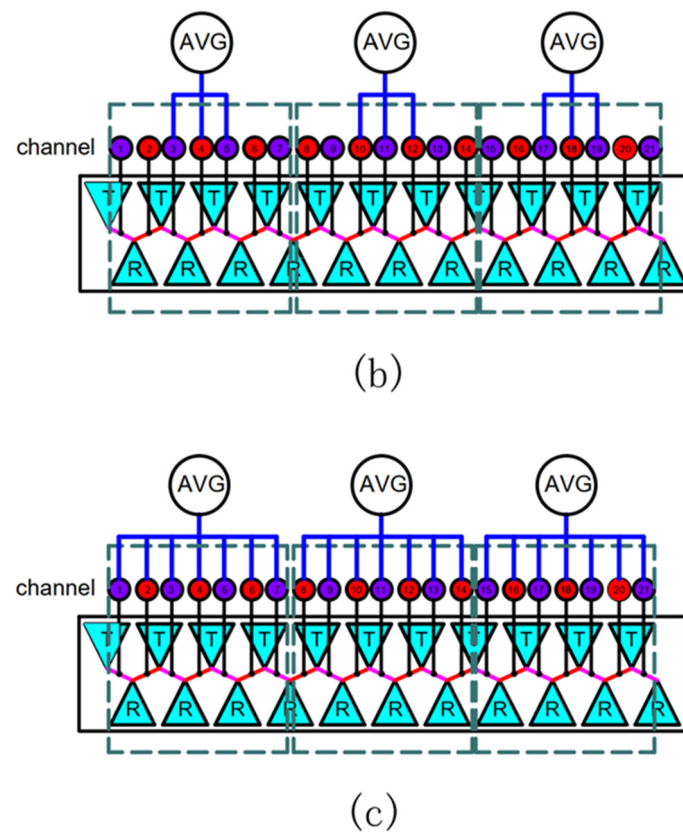


Figure 6. Experimental images of asphalt mixture tests used in this research: (a) Method 1, (b) Method 2, and (c) Method 3.

3.1.1. Method 1

Based on the calculated average of the 10 dielectric constant data points in Method 1 and the one porosity value measured by the non-nuclear density gauge, the best fit was obtained. The specific fit is shown in Figure 7.

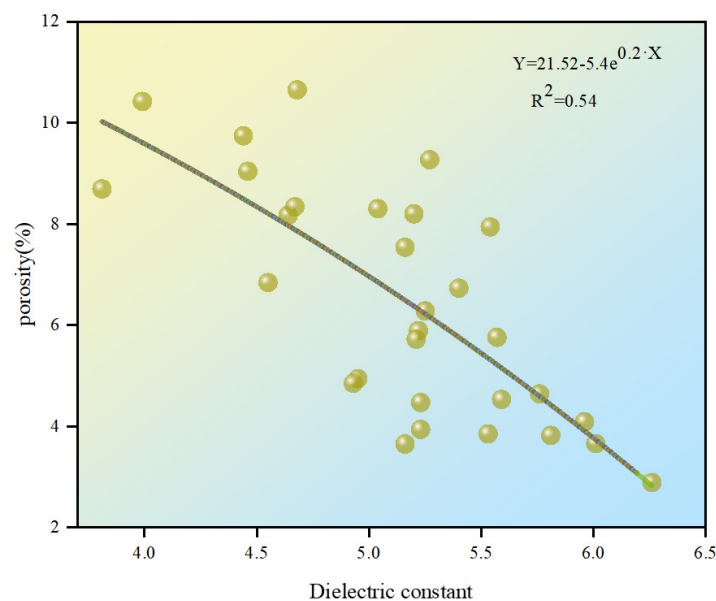


Figure 7. Fitting of the representative values of the dielectric constant obtained by Method 1 and the porosity.

The fitting equation was $Y = 21.52 - 5.4e^{0.2 \cdot X}$, with $R^2 = 0.54$. Based on the low correlation coefficient, it was determined that the fit of the dielectric constant calculated by Method 1 and the porosity was poor. This was mainly because the effective detection width of the radar antenna was 1.5 m, which was equally divided by 21 channels, and the average detection width per channel was 7.14 cm. If only the dielectric constants of the four, 11, and 18 channels were used as representative values, the average detection width per channel was 50 cm. Its effective detection width was diluted by 700.28%, so the dielectric constant–porosity fit was poor.

3.1.2. Method 2

The diameter of the non-nuclear density gauge test chassis was approximately the length of three channels, so a second method of taking the dielectric constant was developed. Data were collected every 10 channels along the length of the test section and the middle three channels of every seven channels in the width direction. A total of 30 data points were averaged, and the average values obtained and the porosity values measured by the non-nuclear density gauge were fitted, as shown in Figure 8.

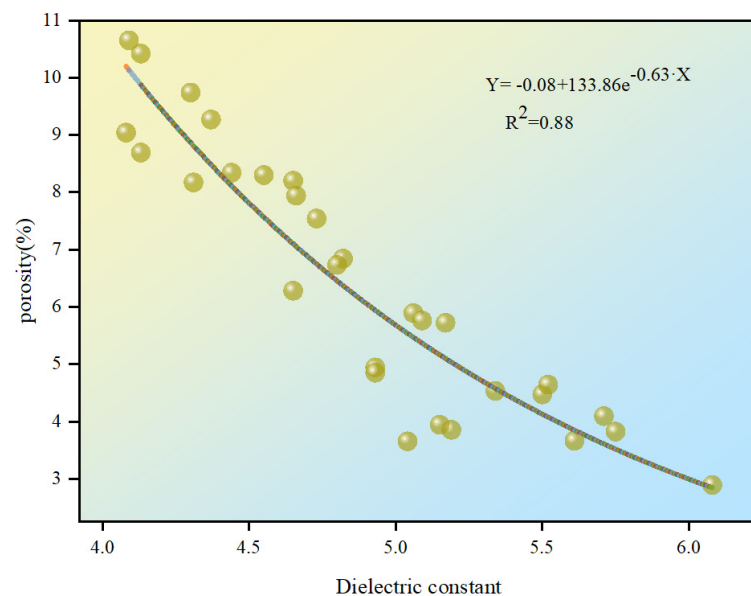


Figure 8. Fitting of the representative values of the dielectric constant obtained by Method 2 and the porosity.

As shown in Figure 8, the fitted model showed a high correlation with the average values of the dielectric constants collected from channels 3, 4, 5, 10, 11, 12, 17, 18, and 19 and the porosity data. The fitted equation was $Y = -0.08 + 133.86e^{-0.63 \cdot X}$, with $R^2 = 0.88$. Mainly during the process of GPR data being collected by the radar antenna and sent to the radar computer for analysis and interpretation, propagation parameters such as the wave velocity, attenuation coefficient, and wave impedance were collected from the scattering data to obtain the quantitative information required for detection. The close spacing of the transmitting and receiving antennas resulted in the unique oscillation characteristics of the GPR data. The area close to the transmitting antenna, where a rapidly decaying low-frequency energy field was generated due to the presence of an electrostatic field and induced electric field (e.g., channels 8 and 9 and passages 13 and 14, channels 6 and 7 and passages 15 and 16), also produced similar oscillations, but relatively weakly. This low-frequency energy field often resulted in a torsional component in the received signal, making the echo signal more variable, and the dielectric constant obtained after unified processing could exhibit large fluctuations and reduced accuracy. This is why the dielectric constants of the middle three channels were chosen to be averaged to avoid this issue.

3.1.3. Method 3

In the third approach, the average value of all the data collected by the GPR in an area of $0.5\text{ m} \times 0.5\text{ m}$ with a total of 70 dielectric constants was calculated. The fit of the average value of the dielectric constant to the corresponding porosity data is shown in Figure 9.

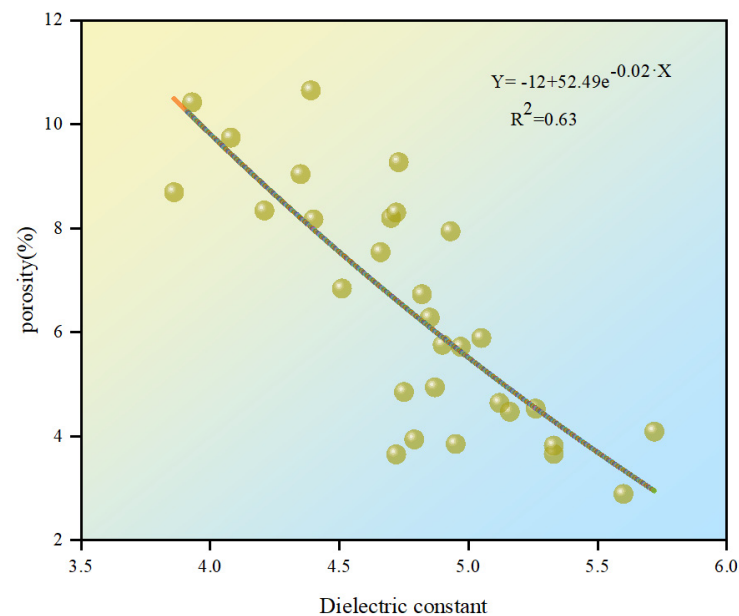


Figure 9. Fitting of the representative values of the dielectric constant obtained by Method 3 and the porosity.

The fitting equation of the average value of the dielectric constant of each seven channels and the porosity measured by the PQI 380 was $Y = -12 + 52.49e^{-0.02 \cdot X}$, with $R^2 = 0.63$. Theoretically, denser test points would better reflect the actual dielectric constant of the asphalt pavement, but this was not observed. The analysis showed that the GPR ground detection exhibited a rapid attenuation of the radar signal as the electromagnetic signal emitted downward from the radar antenna entered the asphalt pavement. As the depth of detection increased, the signal decayed more rapidly. These reflected signals were transmitted back to the radar host via the receiving antenna and needed to be corrected before they could be output. Hence, compensation processing was needed. The general decay of the signal amplitude over time is called the time gain. The time gain process is nonlinear, and a uniform physical model function is required to determine the time gain function. Thus, the transmission times of the radar signals on channels 1, 2, 20, and 21 and channels 10–13 were not the same, and the filtering treatment before and after the time gain treatment changed accordingly, resulting in a large error between the calculated dielectric constant after averaging and the actual dielectric constant of the pavement. Thus, the fitted function correlated poorly with the data.

3.2. Determination of Dielectric Constant Value Method of Asphalt Mixture Pavement

Table 1 can be obtained by summarizing the dielectric constant–porosity formulas obtained from the above test schemes. After a comprehensive analysis, due to the oscillations and time gain processing during the GPR data processing analysis, the correlation between the empirical prediction model relating the dielectric constant and porosity did not become more significant as more dielectric constant data were collected. In this test, the average dielectric constant measured by Method 2 was better correlated with the porosity.

Table 1. Statistical table of dielectric constant–porosity fit data.

	Method 1	Method 2	Method 3
Fitting equation	$Y = 21.52 - 5.4e^{0.2 \cdot X}$	$Y = -0.08 + 133.86e^{-0.63 \cdot X}$	$Y = -12 + 52.49e^{-0.02 \cdot X}$
R^2	0.54	0.88	0.63

4. Asphalt Pavement Construction Quality Evaluation Study

4.1. Engineering Background

To better evaluate the construction quality of asphalt pavement, it is necessary to obtain a large amount of dielectric constant and porosity data. The test was carried out on the intermediate layer of an AC-20 asphalt mixture on a new test road from K12+600 to K12+650.

4.1.1. Materials

The test road section used styrene–butadiene–styrene (SBS, I-D)-modified asphalt according to the Chinese standard JTG E20-2011 [27]. The technical indicators of the asphalt were tested, and the specific technical indicators are shown in Table 2.

Table 2. Styrene–butadiene–styrene (SBS, I-D)-modified asphalt technical specifications.

Items	Test Values	Specification [28]
Penetration (25 °C, 0.1 mm)	52	40–60
Ductility (5 °C, cm)	29.3	≥20
Softening point (°C)	74	≥60
Kinematic viscosity (135 °C, Pa.s)	1.80	≤3

The coarse and fine aggregates were made from high-quality limestone and tested for each functional index according to the Chinese standard JTG F40-2004 [28]. The specific indicators are shown in Tables 3 and 4.

Table 3. Properties of coarse aggregate.

Items	Unit	Limestone Test Results	Specification [28]
Apparent relative density	g/cm ³	2.686	≥2.50
Water absorption	%	0.97	≤3.0
Crush value	%	23.1	≤28
Abrasion value	%	21.6	≤30
Soundness	%	7.0	≤12

Table 4. Properties of fine aggregate.

Items	Unit	Test Values	Specification [28]
Apparent relative density	g/cm ³	2.726	≥2.5
Sand equivalent	%	78	≥60
Soundness	%	14	≤12
Angularity	s	49	≥30

4.1.2. Grading Design of Asphalt Mixes

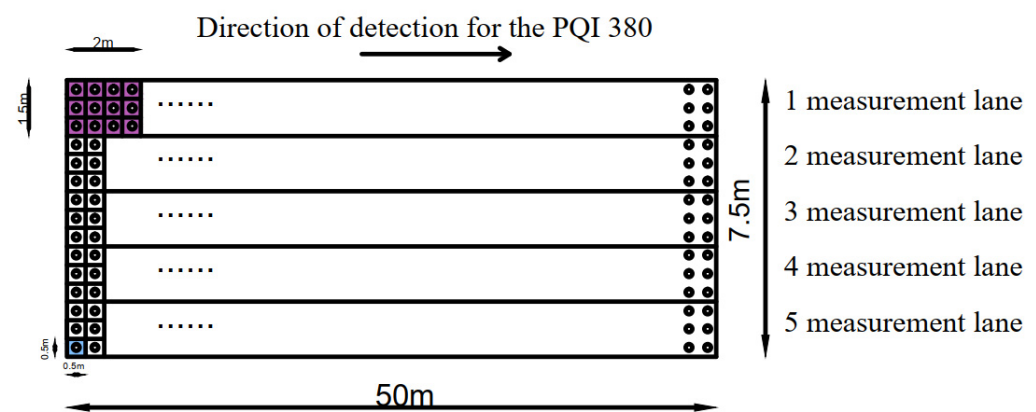
The optimum amount of bitumen for the intermediate layer in the asphalt mixture for this section was determined by Marshall testing to be 4.3%. The maximum theoretical relative density was 2.539 g/cm³, and the gradation composition is shown in Table 5.

Table 5. AC-20 asphalt mixture grading design.

Items	Percentage of Mass Passing the following Sieve Holes (%)										
	19 mm	16 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
Upper limit of gradation	100	92	80	72	56	44	33	24	17	13	7
Lower limit of gradation	90	78	62	50	26	16	12	8	5	4	3
Production mixture ratio	94.6	84.4	74.4	59.2	37.6	25.2	17.8	13.0	9.8	7.5	5.4

4.2. Experimental Design

The length of the designed test section was 50 m, and the width was 7.5 m. The test section was divided into five measurement lanes, each 50 m long and 1.5 m wide, and a grid was drawn with an interval of 0.5 m. In the length direction of the test road, the measurement lane could be divided into 100 grids, and 100 data points could be collected. In the direction of the width, the test section was divided into 15 square grids of 0.5 m $\times$ 0.5 m, and 15 data points were collected. The specific detection path of the PQI 380 is shown in Figure 10. According to the design method, 1500 data points were collected on the test section, and the detection interval was 0.5 m.

**Figure 10.** PQI 380 detection distribution map.

The detection of the GPR is shown in Figure 11. The best detection width of the GPR was 1.5 m, the collection interval was 5 cm, and five measurement lanes were designed. Each measuring channel was 50 m long and 1.5 m wide. In the detection width direction, there were five measurement lanes and 21 channels per lane, and the total width was 7.5 m. Thus, 105 data points could be collected. According to the optimum value scheme for the dielectric constant of the asphalt pavement, in a range of 0.5 m $\times$ 0.5 m, the radar could collect 3 $\times$ 10 valid data points. This method is accurate but requires selecting the required channel data from a large number of GPR data, which is too inefficient. In order to evaluate the construction quality of asphalt pavement more accurately and efficiently, each measurement lane was divided into 25 partial areas, each with a size of 2 m $\times$ 1.5 m. The construction quality of the asphalt pavement was mainly evaluated from the local heavy segregation of the asphalt mixture pavement.

Based on related research and actual engineering experience [29], the area where the porosity of the intermediate layer of the test engineering section was more than 6.5% was defined as severe segregation. Only severe segregation of the asphalt pavement was considered. The 0.5 m $\times$ 0.5 m grid drawn during the detection by the PQI 380 was combined into a 2 m $\times$ 1.5 m local cell, which corresponded to the local area measured by the GPR. The quality of the construction of the asphalt pavement was first evaluated using data collected by a PQI 380, and the GPR collected values according to Method 2. The fitted dielectric constant–porosity model was obtained, and the quality of the asphalt pavement

construction was evaluated. If the findings from the two types of nondestructive testing (NDT) methods were the same, then the above evaluation system could be used to evaluate the quality of the construction of asphalt pavement.

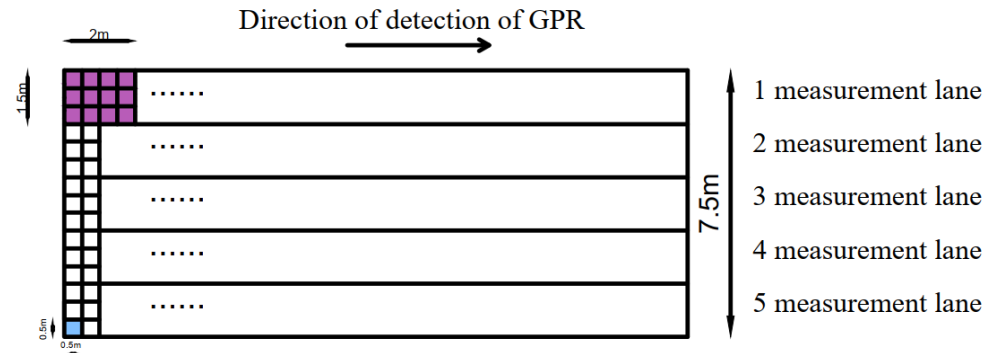


Figure 11. GPR detection distribution map.

4.3. Evaluation of Asphalt Pavement Construction Quality Based on PQI 380

Calibration must be carried out before using the PQI 380 to detect the porosity of the intermediate layer from K12+600 to K12+650. First, a dry and clean area of approximately 1.5 m × 0.75 m was selected on the test section. The area was divided equally into three circles, and data were measured at five locations around each circle using the five-point method of the PQI 380. Then, the height of the core sample at the center of each circle and the laboratory density were measured, and the measured density of the core sample was divided by the density measured by the PQI 380 to obtain the correction coefficient, as shown in Table 6. The 1500 data points collected were corrected by a correction factor, and 12 small grids with lengths of 0.5 m and widths of 0.5 m were combined based on the design plan into a local cell that was 2 m long and 1.5 m wide. It was suspected that severe segregation occurred when the porosity of the intermediate layer of this test section was greater than 6.5%, at which time there would be a certain percentage of detection points with porosities greater than 6.5% at the corresponding position on the asphalt pavement. If the locations of these inspection points were in the same area, it could indicate that the construction quality problem in this area was more severe. The ratio obtained by dividing the number of small grids with porosities greater than 6.5% in a local cell by 12 was defined as the proportion of local severe segregation. The smaller the value of local severe segregation, the better the construction quality became, and vice versa.

Table 6. PQI 380 calibration.

	Core Sample 1	Core Sample 2	Core Sample 3
Center Point 1	2.3725	2.3651	2.3656
Center Point 2	2.3967	2.3854	2.3895
Center Point 3	2.4661	2.3962	2.3864
Center Point 4	2.3732	2.3979	2.3997
Center Point 5	2.3822	2.3921	2.4123
Average	2.3981	2.3873	2.3907
Measured core density	2.396	2.413	2.446
Correction factor	0.9991	1.0107	1.0231
Average of correction factors		1.011	

As shown in Figure 12, when the distance was 0–26 m, most of the local severe segregation in measurement lane 1 was above 0.5, showing a higher horizontal fluctuation trend. The distance was 26–28 m, with a decreasing trend. In the interval between 28 and 50 m, the proportion of local severe segregation fluctuated at a relatively low level. The mean value was 0.39, the extreme difference was 0.67, the maximum value was 0.75

(the horizontal range was 24–26 m), and the minimum value was 0.08 (the horizontal range was 32–34 m). The analysis showed that the pavement had a large porosity at distances of 8–12 m, 16–20 m, and 22–26 m, which may have been due to construction quality problems caused by uneven paver discharge and requires attention when adding the upper surface layer.

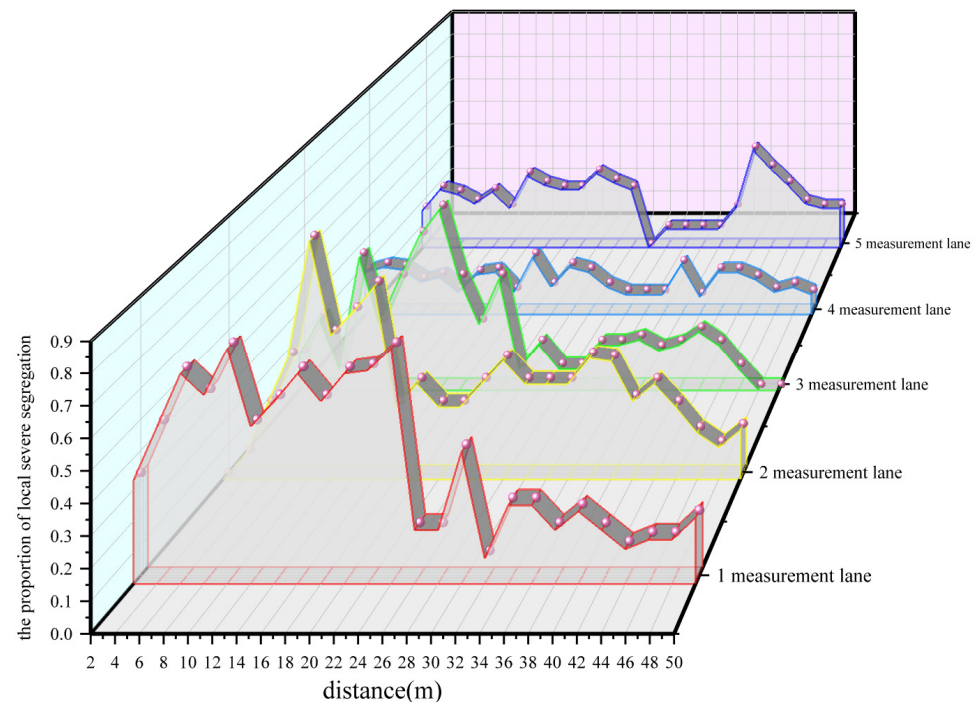


Figure 12. Proportion of local severe segregation on asphalt pavement.

In measurement lane 2, the proportion of local severe segregation at a distance of 0–10 m showed an upward trend, and the peak value was higher. In the range of 10–18 m, there was a step-down trend. Within a distance of 18–50 m, there was a fluctuating trend at lower levels. The mean value was 0.33, and the extreme difference was 0.83, with a maximum value of 0.83 (the horizontal range was 8–10 m) and a minimum value of 0 (the horizontal range was 0–2 m). The analysis showed that at distances of 8–12 m and 14–16 m, the pavement had a large porosity and heavy segregation, and the construction quality of the pavement was poor.

In measurement lane 3, the proportion of local severe segregation at a distance of 0–16 m underwent a step-like upward trend. At a distance of 16–24 m, there was a step-down trend. At distances of 24–42 m, the trend fluctuated at lower levels. There was a decreasing trend in the distance range of 42–50 m. The mean value was 0.23, and the extreme difference was 0.68, with a maximum value of 0.68 (in the horizontal range of 14–16 m) and a minimum value of 0 (in the horizontal range of 46–50 m). The analysis showed that, at distances of 8–12 m and 14–16 m, the pavement had a large porosity and heavy segregation, and the construction quality of the pavement was poor.

In measurement lane 4, the overall detection of the proportion of local severe segregation in the region showed a steady fluctuating trend with no particularly prominent points. The mean value was 0.14, the extreme difference was 0.16, the maximum value was 0.23 (the horizontal range was 34–36 m), and the minimum value was 0.07 (the horizontal range was 36–38 m). The overall porosity of measurement lane 4 was under control, and there were few areas where heavy segregation occurred, so the construction quality was good.

In measurement lane 5, the proportion of local severe segregation at a distance of 0–26 m fluctuated at a level near 0.2. When the distance was 26–28 m, it showed a sudden downward trend. A rising trend appeared at distances of 28–40 m. In the range of 40–50 m, there was a downward trend. The mean value was 0.21, and the extreme difference was

0.42, with a maximum value of 0.42 (in the horizontal range of 38–40 m) and a minimum value of 0 (in the horizontal range of 26–28 m). The porosity of the asphalt pavement was greater at distances of 0–26 m and 38–46 m than in the corresponding areas of measurement lane 4, which had a greater degree of heavy segregation. Thus, the construction quality was worse than that in measurement lane 4.

The mean values of the proportion of local severe segregation for the above five measurement lanes were in the order of measurement: lane 4 < measurement lane 5 < measurement lane 3 < measurement lane 2 < measurement lane 1. Most of the data from channel 4 were smaller than the those in the other four channels and more evenly distributed throughout the channel, with less severe segregation. The extreme differences in the proportion of local severe segregation for the measurement lanes were in the order of measurement: lane 4 < measurement lane 5 < measurement lane 1 < measurement lane 3 < measurement lane 2. The range of fluctuations in the proportion of local severe segregation was minimal for measurement lane 4 and was more evenly distributed throughout the measurement lane. A comprehensive analysis of the results of the five test tracks showed that the construction quality of measurement lane 4 was the best and that the construction quality of measurement lanes 1 and 2 was poor.

4.4. Evaluation of Asphalt Pavement Construction Quality Based on GPR

The object of the GPR study was also the intermediate layer from K12+600 to K12+650. The optimal detection width for GPR is 1.5 m, and the optimal acquisition interval is 0.05 m. The designed detection method is shown in Figure 11. On the test road, the GPR detected a total of five measurement lanes, of which 21 data points could be detected in the direction of the width of each measurement lane. One measurement lane of the GPR could collect up to 1000 data points in each measurement lane length. Within the detection range of $0.5\text{ m} \times 0.5\text{ m}$ of the PQI 380, the GPR could collect 30 data points. To evaluate the construction quality of the intermediate layer in asphalt pavement more accurately, a partial area of $1.5\text{ m} \times 2\text{ m}$ was used as the study area for the dielectric constant of the asphalt pavement, which corresponded to the partial area merged with the PQI 380, and the average value of the local dielectric constant was used to evaluate the construction quality of the asphalt pavement.

In this study, areas with porosities greater than 6.5% were defined as severely segregated. By fitting the calculated dielectric constant–porosity prediction model based on the second method of taking the dielectric constant and converting it, it was concluded that severe segregation occurred when the dielectric constant of the asphalt pavement was greater than 5.167. If the data points with a dielectric constant greater than 5.167 were too concentrated in one area, it could be assumed that there was a serious quality problem.

According to Figure 13, the average value of the local dielectric constant for measurement lane 1 fluctuated relatively widely over a distance of 4–36 m. There was essentially no severe segregation in the range of 36–50 m. The overall mean value of the average value of the local dielectric constant values was 4.7596, with a maximum value of 6.59 and a minimum value of 3.5. The area of severe segregation detected by the GPR essentially covered the area of severe segregation detected by the PQI 380. At a distance of 34–36 m, the PQI 380 did not reflect the severe segregation in this area due to the limited number of data points that it collected.

In measurement lane 2, the average value of the local dielectric constant was relatively small over a distance of 0–8 m. The average values of the local dielectric constant values were relatively large (severe segregation) over distances of 8–16 m and 26–46 m. The overall mean of the average values of the local dielectric constants was 4.8584, the maximum value was 7.41, and the minimum value was 3.73. The large variations in the overall mean value of the dielectric constant could indicate that the construction quality of this test measurement lane was unstable. This was consistent with the determination of the PQI 380.

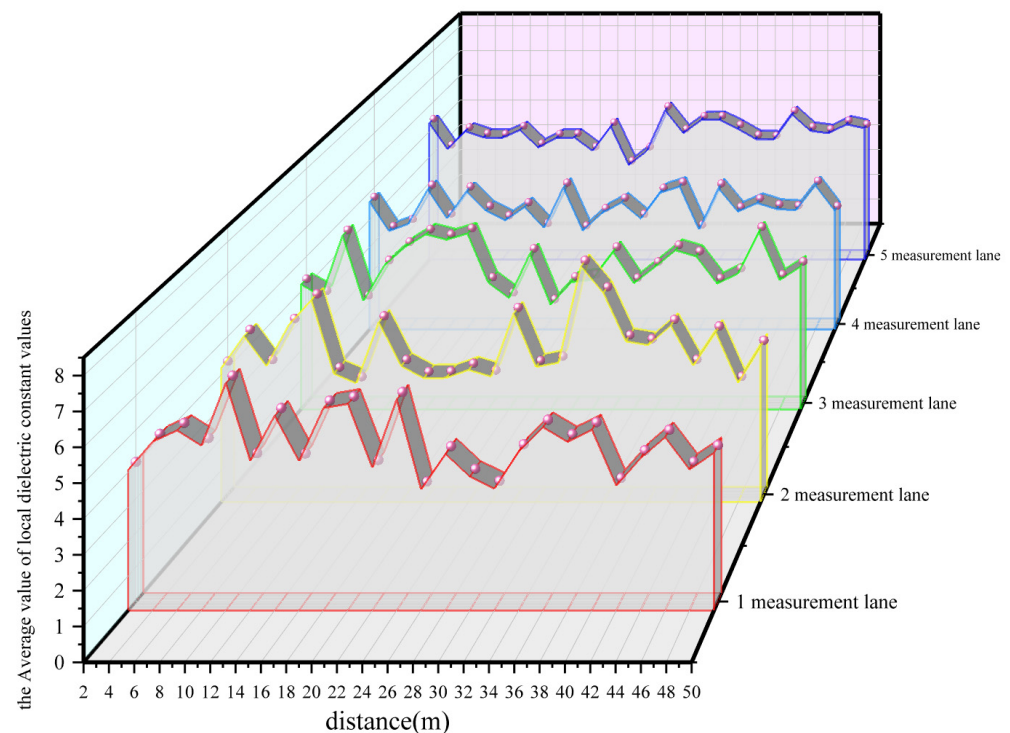


Figure 13. Distribution of the average values of the local dielectric constants in asphalt pavements.

In measurement lane 3, the average value of the local dielectric constant within the range of 6–20 m fluctuated significantly, and there were many severe segregation phenomena. In the range of 32–38 m and 42–46 m, the evaluation index of the PQI 380 did not reflect the severe segregation at this specific location. This may have been because the PQI 380 only measured data at the center of a $0.5 \text{ m} \times 0.5 \text{ m}$ square grid, and edge locations were not examined. It is possible that the midpoint value was not representative of the entire small grid with severe segregation.

The average values of the local dielectric constant values for measurement lane 4 were generally stable with small fluctuations. The overall average was 4.43, the maximum value was 5.25, and the minimum value was 3.59. These are the same results as those obtained by the PQI 380.

The average values of the local dielectric constant values for measurement lane 5 were large. The average over a distance of 30–42 m was 5.15, which was close to the dielectric constant of 5.17 when severe coarse segregation occurred. The overall mean of the average values of the local dielectric constant values was 4.91, the maximum value was 5.66, and the minimum value was 3.7. Although some of the local mean values of the dielectric constants for measurement lane 5 exceeded 5.17, they were more stable overall, with some fluctuations. The data points were evenly distributed throughout the measurement lanes, and the overall construction quality was better than that for measurement lane 2.

Based on Figures 12 and 13, the test results of the nucleus-free density meter designed to evaluate the quality of asphalt pavement construction were compared to the test results obtained by GPR and verified, and the same test conclusions were found. This demonstrated that GPR and the PQI 380 could be used to evaluate the asphalt pavement construction quality more quickly, efficiently, and accurately. The GPR used a full detection range and was more efficient. The PQI 380 used a single point of detection; its detection data were accurate but inefficient. In an area of $0.5 \text{ m} \times 0.5 \text{ m}$, the PQI 380 could only collect data from one midpoint, and the edges could not be collected. For example, no construction quality problems were detected between 34 and 36 m on measurement lane 1. Furthermore, no quality problems were detected between 32 and 38 m and between 42 and

46 m on measurement lane 3. However, the actual pavement had a large porosity, and the construction quality was unstable.

When carrying out actual asphalt pavement construction quality inspection, if the inspection area is small, the construction quality of the asphalt pavement can be evaluated directly using a PQI 380 based on the proportion of local severe segregation. When the area of the pavement to be tested is large, first, a 5-m test section is selected and porosity data are collected and analyzed using the PQI380. GPR is used to collect the dielectric constant data based on the second method of taking the dielectric constant and establishing a dielectric constant–porosity empirical prediction model. The GPR is then used to detect the whole road surface, and finally, the average value of the local dielectric constant values is used in the data processing process to evaluate the construction quality of the asphalt pavement.

5. Conclusions

In this paper, we proposed the use of a PQI 380 with GPR as a nondestructive testing tool for more efficient and accurate inspection of asphalt pavement construction quality. A nondestructive testing evaluation system for the quality of asphalt pavement construction was designed and validated, allowing the following conclusions to be drawn.

(1) The optimization of the dielectric constants collected by the GPR led to the identification of a new choice of values for the dielectric constants of the radar antenna channels. Every 10 data points along the length of the test were collected, and the average value of the dielectric constant of the middle three channels of every seven channels in the radar width direction was computed. A total of 30 data points were averaged.

(2) The data measured by the PQI 380 and GPR were analyzed and fitted to the dielectric constant and porosity data, and a corresponding dielectric constant–porosity prediction model was developed: $Y = -0.08 + 133.86e^{-0.63 \cdot X}$, with $R^2 = 0.86$. By analyzing and comparing different methods of obtaining the dielectric constant, this prediction model was found to provide the best fit.

(3) We proposed using the average value of the local dielectric constant to evaluate the construction quality of asphalt pavement in the results measured by GPR. For the detection of the PQI 380, we proposed using the proportion of local severe segregation to determine the problem of road segregation and further evaluate the construction quality of asphalt pavement. The results of the two NDT methods were identical: the best construction quality was found on measurement lane 4, and the worst construction quality was found on measurement lane 2.

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