



Journal of Materials and Engineering Structures

Research Paper

Application of Non-destructive testing methods for asphalt pavement density measurement on the Mai Son–NH45 expressway segment, Vietnam

Xuan Chieu Luong ^a, Quang Phuc Nguyen ^a, Tien Dung Chu ^{a,*}

^a Department of Highway and Traffic Engineering, Faculty of Civil Engineering, University of Transport and Communications, No. 3 Cau Giay Street, Lang Thuong Ward, Dong Da District, Hanoi, Vietnam

ARTICLE INFO

Article history:

Received : 8 November 2024

Revised : 22 December 2024

Accepted : 28 December 2024

Keywords:

Asphalt concrete

In-situ density

Non-destructive testing

PaveTracker 2701 - B

ABSTRACT

In the last few years, the development of expressways in Vietnam has been rapid. Asphalt concrete (AC) is the most widely used material for expressway pavement due to its widespread availability and favorable characteristics. The quality of pavement not only influences traffic safety but also impacts the longevity of the expressway. Therefore, quality control (QC) as well as quality assurance (QA) of AC pavement are crucial during construction. In-situ density, which indicates the degree of compaction, must be quickly and accurately predicted for effective QC and QA. Non-destructive testing (NDT) methods offer rapid, accurate, and extensive density measurements. However, NDT has not been widely adopted in Vietnam, leading to doubts among users regarding their operational principles, accuracy of predictions, and reliability. This paper reviews global practices in NDT methods for measuring AC density, offering an in-depth analysis of current techniques and highlighting their strengths, limitations, and relevance to road construction QC. Additionally, it explores the application of NDT equipment, specifically the PaveTracker 2701, on the Mai Son – NH45 expressway, proposing its potential for broader use in Vietnam.

1 Introduction

Vietnam has recently experienced significant growth in its expressway network, which now extends to approximately 1,900 km as of 2023. The quality of pavement is crucial for maintaining the operational efficiency, safety, and durability of these roads. Asphalt concrete (AC) is widely favored for highway and expressway pavement in Vietnam due to its numerous advantages. Consequently, there has been an increasing emphasis on materials, construction technology, quality control (QC), and quality assurance (QA) during AC pavement construction to ensure project durability and excellence. Specifically, in-situ density, a crucial indicator of compaction, requires rapid and precise prediction to maintain construction progress and project quality. If the target density is not achieved—whether due to under-compaction or over-

* Corresponding author. Tel.: +84 912777219.

E-mail address: dungchu@utc.edu.vn

compaction—it can lead to various pavement damages during operation, including moisture damage [1-3], cracking, ravelling [4, 5], rutting, bleeding, and other issues [6].

The traditional method for assessing in-situ density, such as the coring method, has been commonly employed worldwide due to its perceived accuracy [7]. However, despite its precision, the coring method has inherent limitations. It disrupts pavement continuity, making it susceptible to water seepage and subsequent issues like rutting and potholes, which incur additional costs for maintenance and rehabilitation [8]. Furthermore, the process of coring and filling is labor-intensive, and the limited number of samples obtained through drilling is inadequate for evaluating construction quality over time and ensuring uniformity. These factors can lead to delays in traffic opening times and prolonged traffic interruptions.

To address these shortcomings, non-destructive testing (NDT) methods have been developed and commonly utilized for pavement density measurement. These techniques offer valuable insights into pavement quality and integrity without causing damage. By leveraging various technologies, they assess the density of pavement materials and ensure compliance with specified requirements.

Despite the advantages of NDT methods, their adoption in Vietnam remains limited, such as Da Nang - Quang Ngai expressway and National Highway No. 6. [9], leading to skepticism among users regarding their working principles, prediction accuracies, and reliabilities. This paper aims to review current practices of NDT methods for AC density measurements worldwide. Additionally, it explores the potential application of non-destructive testing equipment, particularly the PaveTracker 2701, on the Mai Son – NH45 expressway, suggesting its viability for implementation in Vietnam.

2 Literature review

2.1 NDT methods

NDT methods have been extensively developed and globally adopted for measuring AC pavement density. These techniques play a critical role in the construction and maintenance of road infrastructure, ensuring that pavements meet quality standards and perform optimally over their lifespan. This section provides a summary of typical NDT methods utilized for evaluating AC pavement densities, highlighting their importance in facilitating efficient and effective pavement management practices.

The nuclear density gauge (NDG) has long been a standard tool for estimating the in-situ density of AC) since its introduction in the 1950s. NDG measures density by utilizing the principles of nuclear physics. It involves the use of a portable device containing a small radioactive source, typically cesium-137 or americium-241, which emits gamma radiation. The gauge measures the amount of radiation that is scattered or absorbed by the pavement material, providing an indication of its density. This method is particularly common in the US, as it provides a non-destructive approach and offers reasonably accurate estimates of in-situ AC density measurements [6]. Despite its advantages, the NDG poses potential hazards due to the radioactive materials used in the device. As a result, special precautions are required for storage and transportation [10], and the gauges must be operated by licensed personnel [6].

Another approach capable of overcoming the limitations of Nuclear Density Gauges (NDG) is Ground Penetrating Radar (GPR). Utilizing short pulses of electromagnetic waves spanning a frequency range of 100–5,000 MHz, GPR detects subsurface features and properties, including pavement density. These pulses bounce back to the antenna with varying amplitudes and arrival times, correlating with the dielectric constants of the material layers. At material interfaces, a portion of the energy reflects while another portion absorbs, contingent upon the dielectric contrast among materials. Through analyzing these reflections of radio waves from distinct layers within the pavement structure using one-dimensional electromagnetic wave propagation theory, GPR can gauge the density of the materials (see Fig. 1a). Since the GPR operates through the transmission and reception of electromagnetic waves, it offers the advantages of completely bypassing safety concern. As illustrated in Fig. 1b, two types of GPR antennas, air-coupled and ground-coupled, are commonly applied. Although the ground-coupled antenna remains adjacent to the surface during surveying, allowing more electromagnetic wave energy to reach the pavement structure and achieving deeper penetration than the air-coupled system—where approximately 40 to 50% of the energy is lost at the air-pavement interface—the survey speed of the ground-coupled antenna, which cannot exceed 10 km/h, is slightly lower compared to that of the air-coupled antenna [11, 12].

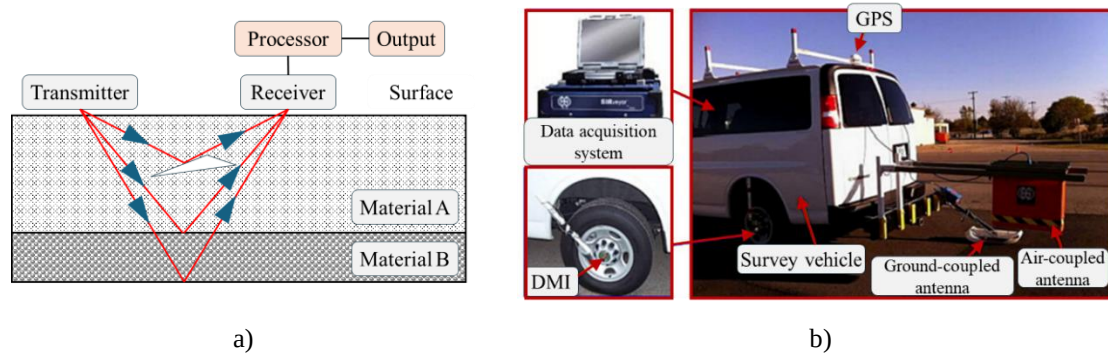


Fig. 1 – a) Principle of testing with the GPR system [13], b) Air-coupled antenna and ground-coupled antenna [14].

Similar to GPR, non-nuclear density gauges (NNDG) have been developed to measure AC pavement density, avoiding the hazardous issues associated with radioactive materials used in NDG. The operation of NNDG is straightforward and specialized training is not required. Fig. 2 illustrates two typical products that have recently emerged from NNDG: the PQI (Pavement Quality Indicator) and PaveTracker. Both PQI and PaveTracker predict AC pavement density by measuring its dielectric constant. In this process, illustrated in Fig. 2c, the transmitter ring generates electromagnetic waves while the receiver ring captures the reflection intensity. Both components are arranged axis-symmetrically within the gauge. The dielectric constant changes measured by NNDG are then converted to AC pavement density. To ensure accuracy, the density measured by the NNDG should be calibrated to the actual pavement coring densities. By applying calibration and correction factors, direct density measurements can be obtained.

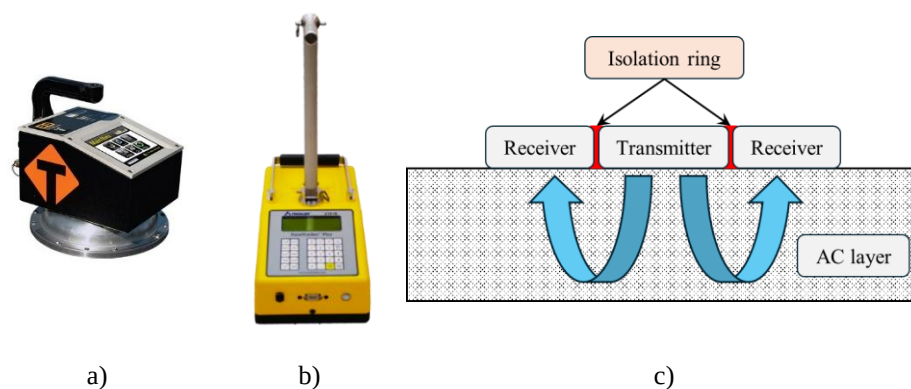


Fig. 2 – a) PQI380 (© Atlantic supply) b) PaveTracker TM Models 2701-B Plus (© Troxler Labs); c) Principle of non-nuclear density gauges (NNDG)

2.2 The factors affecting accuracy of density measurement

2.2.1 Ground Penetrating Radar (GPR)

As outlined in Wang et al. [15], several factors can influence the accuracy of density measurements obtained through GPR. Notably, the amplitude of the impacting surface reflection impacts the accuracies of both the AC layer's dielectric constant and density measurements. The amplitude may vary due to interference from reflections at the bottom of the AC layer, especially when the GPR signal wavelength closely matches the layer's thickness. To address this issue, advanced algorithms known as digital signal processing (DSP) have been developed, including matched filtering, non-linear optimization, and sub-space decomposition. These algorithms are designed to address issues related to overlapping reflections, thereby enhancing the accuracy of density measurements obtained via GPR.

Moreover, during the compaction process, surface moisture resulting from water spray can impact the reflection intensity. Nozzles installed on rollers continuously spray water onto the wheels to prevent the AC mixture from adhering while compacting. Consequently, some residual water remains on the pavement surface, increasing the surface reflection

intensity due to its higher dielectric constant compared to that of the AC mixture. This augmentation is observed across a certain frequency bandwidth in comparison to dry conditions. To mitigate the impact of surface moisture, the overlapping bandwidth between dry spectral signals and surface moisture is utilized, along with automatic signal processing methods for modification.

Additionally, during continuous GPR surveys, significant oscillations in the antenna position can affect the signal's reflection intensity. From the perspective of antenna radiation theory, when the distance between the antenna and the pavement surface is increased, the reflection intensity diminishes. Consequently, rapid oscillations of the air-coupled antenna produce higher frequency noise and outlier values not only in the estimated dielectric constant but also in the predicted density profiles. This can mask the actual distribution of density variations, making it difficult to identify areas of over-compaction or under-compaction. To tackle this issue, researchers have developed DSP techniques to reduce the impact of vibrations.

2.2.2 Non-nuclear density gauges (NNDG)

Wang et al. [15] conducted a comprehensive review focusing on the impact of environmental factors, particularly temperature and moisture conditions, on the accuracy of NNDG measurements. They have conclusively shown that mat temperature plays a crucial role in determining the compaction quality of AC. That is the density measured from both types of NNDG (PQI and PaveTracker), tends to increase as the mat temperature rises. This correlation underscores the importance of considering temperature variations during pavement compaction processes, as it directly impacts the accuracy of density measurements obtained through NDG technology. In addition to temperature, the presence of moisture is another significant factor influencing NNDG results, as the dielectric constants of the AC mixture and air are considerably greater than that of water. The existence of a surface moisture film, particularly when applied to uncompacted material, can lead to errors in density predictions obtained from NNDG. Moreover, internal moisture within the pavement structure also exerts a substantial impact on the accuracy of NNDG measurements. These factors emphasize the importance of considering moisture effects when conducting NNDG density assessments, as they can significantly influence the reliability and accuracy of the results. Therefore, maintaining a stable surrounding temperature and ensuring low-moisture testing conditions is crucial for obtaining precise density measurements with NNDG. These measures are crucial for minimizing errors and obtaining reliable density data during pavement construction and quality control processes.

Various factors affecting the accuracy of NNDG density measurements related to AC mixtures have been examined [15]. These factors include aggregate distribution, maximum particle size, binder proportion, and type of mixture. They concluded that the aggregate source, gradation, and maximum size significantly influence NNDG density measurements, while the effect of asphalt binder content was found to be negligible. Therefore, it is recommended that mix-specific calibration is a necessary component of NNDG operating procedures. Calibration at both the mixture and project levels is considered essential for the effective application of NNDG. It is worth noting that a strong correlation in density measurements can be established between core/nuclear methods and NNDG technology through composition-specific calibration, provided that uniform temperature and moisture levels are maintained at each testing location. Statistical evaluation revealed high accuracy in AC mixture measurements using offsets or mix calibration, emphasizing that the adjustment process is critical when applying NNDG technology.

Furthermore, the examination of NNDG results obtained in several operational directions, either perpendicular or parallel to the direction of compaction, demonstrated no significant discrepancy in density measurements. This was attributed to the axially symmetric configuration of the transmitter and receiver rings in the NNDG system. Overall, the findings underscore the necessity of mix-specific calibration and highlight the importance of maintaining consistent testing conditions for accurate density measurements using NNDG technology [15].

3 Application of NDT in Mai Son – NH45 expressway

3.1 Mai Son – NH45 project

The Mai Son - NH45 Expressway spans a length of 63.37 km and is a vital segment of the North-South Expressway system. It traverses the eastern regions of Ninh Binh and Thanh Hoa provinces. Phase 1 of the project involves constructing a 4-lane road surface with emergency stopping points arranged at intervals of 4 - 5 km along the route and a maximum speed limit of 90 km/h.

3.2 Calibration of PaveTracker 2701 – B

Prior to using the PaveTracker device for density measurements of the AC pavement across the project, calibration is necessary to improve accuracy. There are two methods to adjust the measurement: density offset and mix calibration. This paper adopts the first method, density offset calibration. The process involves the following steps: (1) Measure the AC density using the PaveTracker. (2) Determine the AC reference density through coring (ensure the coring sample is taken from the same location where the PaveTracker measured the density). (3) Calculate the density offset by subtracting the PaveTracker-measured density from the reference density. (4) Input the density offset into the PaveTracker software [16]. It is important to note that at least three test locations are required, and at each location, a minimum of four measurements by the PaveTracker is needed to calculate the average results [17].



Fig. 3 – Measurement of density by PaveTracker 2701 – B and Coring for calibration

The measured density (via PaveTracker) and the reference density (from coring) were obtained at six testing locations in Package 11 (see Fig. 3), with calibration results presented in Table 1. Remarkably, two separate density offsets were required for the calibration of the AC12.5 mixture using SBS, as two distinct AC mixtures were used in different segments, each constructed by a different contractor.

For the first segment (Km297+000 to Km301+000), calibration was performed at Km300+585, located on the right side of the expressway, 6.7 meters from the centerline. Three testing locations, spaced over a 3-meter section along the expressway, were measured using the PaveTracker. Asphalt concrete samples were then drilled at these locations according to TCVN 13348:2021 [17]. However, it was observed that drilling multiple samples in a small area could compromise the quality of the AC surface.

Therefore, for the second segment (Km289+500 to Km297+000), three different locations (see Table 1), situated on the left side of the expressway but within the same AC mixture, were selected to minimize potential pavement distress.

To ensure that the densities obtained from both conventional and PaveTracker are not significantly different, a paired sample T-test of means was performed. With a t-value of 1.54 and a p-value of 0.221, we fail to reject the null hypothesis, suggesting that the densities obtained from both methods are not significantly different. This indicates that the density measured by the PaveTracker is reliable. Additionally, as shown in Table 1, the average density offsets were calculated for each segment and input into the PaveTracker software for density measurements across the entire project.

Notably, in the following discussion, the term 'relative density' is used instead of 'density.' Relative density is defined as the ratio (expressed as a percentage %) of field density to the maximum density determined in the laboratory under specific, controlled compaction conditions. In this paper, the laboratory maximum densities at the monitoring and testing area were provided by the contractors and supervision consultant to calculate the relative density using the PaveTracker 2701-B.

3.3 PaveTracker 2701 – B Application

Following calibration, the PaveTracker 2701-B was employed to assess the in-situ density of AC12.5 incorporating SBS additives along the road stretch from Km289+500 to Km301+00 (see Fig. 4). A total of 108 locations were inspected, revealing that 8 locations did not meet the technical density requirements. Specifically, 4 locations on the left side between

Km289+567 and Km289+582.5, and 4 locations on the right side between Km300+509.6 and Km300+530.3, exhibited density deficiencies.

Table 1 – Coring density and PaveTracker density.

No.	Stattion	Location	Reference density (g/cm³)		Measured density (g/cm3)				Density offset (g/cm³)	
			Coring	Average	PaveTracker		Average			
Segment 1: Km297+000 to Km301+000										
1	Km300+585	R - DC 6,7m	2.325	2.333	2.350	2.352	2.371	2.363	2.369	-0.036
2			2.347		2.365	2.378	2.397	2.400		
3			2.327		2.361	2.373	2.359	2.359		
Segment 2: Km289+500 to Km297+000										
4	Km295+577	L - DC 3,0m	2.417	2.420	2.353	2.366	2.352	2.353	2.358	0.063
5	Km295+577	L - DC 6,4m	2.416		2.351	2.362	2.353	2.356		
6	Km296+425	L - DC 2,4m	2.427		2.358	2.362	2.352	2.372		

Note:

R = Right side of expressway

L = Left side of expressway

DC = Distance to the Center of expressway

Subsequently, the PaveTracker 2701-B was utilized to identify areas necessitating removal and re-paving. Then, control charts are used to assess whether the AC density and compaction process remain stable and under control or if adjustments or re-paving are necessary. In this paper, we applied a type of control chart known as the Individual Moving Range (I-MR) chart. The I-MR chart consists of two parts: the Individual Chart (I Chart), which shows individual data points, and the Moving Range Chart (MR Chart), which displays range values (Moving Range) calculated between consecutive individual points ($x_i - x_{i-1}$). If data points are outside the Control Limits, it indicates that the process is unstable. The center line, Upper Control Limits (UCL), and Lower Control Limits (LCL) are calculated using the equations using the equations provided in Table 2.



Fig. 4 – PaveTracker 2701-B on testing locations

Table 2 – Equations for estimation of center line, UCL and LCL for I-MR Chart

No.	Control Limits	I Chat	MR Chart
1	Center line	$\bar{X} = \frac{\sum_{i=1}^k x_i}{k}$	$\overline{MR} = \frac{\sum_{i=1}^k x_i - x_{i-1} }{k - 1}$
2	Upper Control Limits	$\bar{X} + 3\sigma$	$\bar{X} + 3\sigma$
3	Lower Control Limits	$\bar{X} - 3\sigma$	0

Note:

x_i = value at point i

k = number of data points

σ = standard deviation

This paper utilized Minitab 18 software to conduct the statistical tests and generate the I-MR Charts, as shown in Fig. 5 and Fig. 6. It is noteworthy that various tests, numbered from Test 1 to Test 8, are conducted in Minitab to identify special causes and determine which observed data require further investigation. The red dots in the I-MR Charts highlight the points that may need investigation, and the numbers next to them represent the corresponding test number.

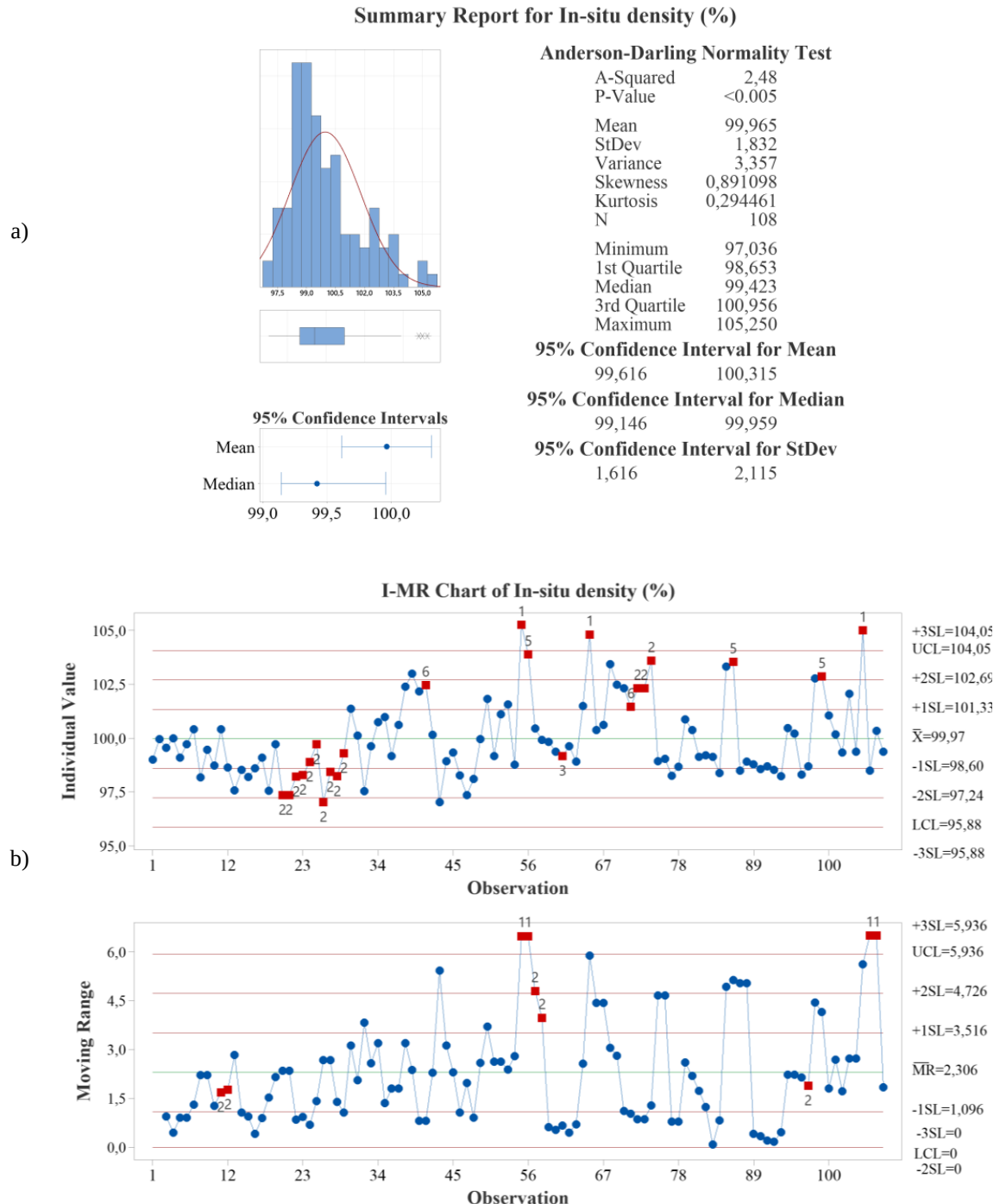


Fig. 5 – a) Summary report; b) I-MR Chart of in-situ density

As evident from Fig. 5, the relative density results obtained from the Pavetracker 2701-B indicated a consistent density throughout the construction process, with an average value of 99.97%. Three months later, density measurements were conducted again at the same 108 locations. The two-sample t-test results (depicted in Table 3) demonstrated no statistically significant difference between the density immediately after re-paving and the density measured after 3 months.

This indicates that the effective asphalt mixture and proper compaction process maintained a density after 3 months comparable to the initial in-situ density.

Table 3 – Two-Sample T-test for the Mean of In-situ density after 3 months and In-situ density

No.	Statistics	In-situ density after 3 months	In-situ density
Individual sample			
1	Sample size	108	108
2	Mean	100.02	99.97
3	95% Upper bound	100.30	100.26
4	Standard deviation	1.78	1.83
Difference Between Samples*)			
1	Difference	0.054	
	95% Upper bound	0.460	

Note*) Difference = Density after - In-situ density

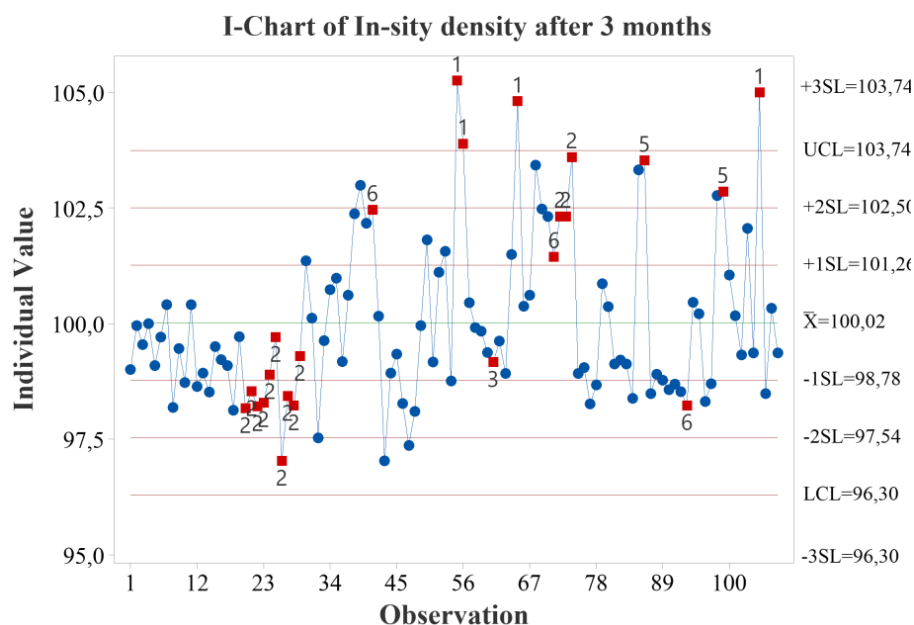


Fig. 6 – I Chart of density by PaveTracker 2701-B after 3 months

Furthermore, the relative density data collected after 3 months were plotted on a I Chart (Fig. 6). The I Chart affirmed the achievement of uniform density in the AC construction process, with an average value of 100.02%. The majority of points fell within the range of $\pm 2\sigma$, indicating consistency, with only a few points exceeding $\pm 3\sigma$.

4 Conclusion

This paper presents a comprehensive overview of non-destructive testing (NDT) methods used to measure the density of asphalt concrete (AC) pavement, focusing on traditional and emerging technologies such as the nuclear density gauge (NDG), Ground Penetrating Radar (GPR), and non-nuclear density gauges (NNDG). Historically, the NDG has been a widely adopted method due to its reliability; however, it comes with limitations, including regulatory challenges due to radioactive materials, safety concerns, and logistical constraints in handling and usage. To address these limitations, GPR and NNDG methods have emerged, utilizing electromagnetic waves that allow for greater ease of use and reduced regulatory burden. The ability of GPR and NNDG to perform density measurements without the complications associated with nuclear technology has positioned them as promising alternatives for modern pavement assessment.

This paper further examines key factors influencing the accuracy and consistency of GPR and NNDG, such as surface conditions, material properties, calibration techniques, and environmental variables. In particular, the study investigates the use of a specific non-nuclear density gauge, the PaveTracker, in the Mai Son - NH45 Expressway project. Four strategically chosen testing locations were used to calibrate density measurements from the PaveTracker against reference density values obtained through core sampling, a process that provided a benchmark for accuracy. Calibration results indicated no significant discrepancy between PaveTracker measurements and core-derived densities, supporting the reliability of the PaveTracker for density assessment.

During the project, density measurements were taken at 108 testing sites across the construction phase and again three months post-construction to evaluate any changes over time. A two-sample t-test was applied to determine whether any statistically significant difference existed between the density measurements taken at these two stages. The test results showed no statistically significant difference, suggesting that the density remained consistent and uniform over the evaluation period. To further validate uniformity, an I-MR (Individual-Moving Range) Chart was generated using Minitab software, which confirmed the consistency of density values throughout the AC pavement construction process.

The successful use of the PaveTracker in obtaining consistent and accurate density measurements on the Mai Son - NH45 Expressway demonstrates its potential for future infrastructure projects in Vietnam. By eliminating the complexities associated with nuclear technology, such as regulatory constraints and safety concerns, the PaveTracker and similar non-nuclear density gauge (NNDG) methods offer a practical and reliable solution for quality control (QC) and quality assurance (QA) in pavement construction. This study advocates for the broader adoption of NNDG technology in Vietnam, supporting evolving safety standards and addressing the growing need for efficient, non-invasive pavement assessment methods that enhance construction oversight and long-term pavement performance.

Further research could explore additional applications of the PaveTracker, including density assessments at critical pavement sections like longitudinal joints, where achieving compaction consistency can be challenging yet is essential for pavement durability. Inadequate density at these locations may increase the permeability of AC, potentially leading to damage over time. By focusing on these high-impact areas, future studies could provide valuable insights into best practices for density measurement, ultimately contributing to more resilient and cost-effective infrastructure.

REFERENCES

- [1]- S. Xu, F. Xiao, S. Amirkhanian, D. Singh, Moisture characteristics of mixtures with warm mix asphalt technologies – A review. *Construction and Building Materials*, 142 (2017) 148-161. doi:10.1016/j.conbuildmat.2017.03.069.
- [2]- F. Xiao, V.S. Punith, B.J. Putman, Effect of Compaction Temperature on Rutting and Moisture Resistance of Foamed Warm-Mix-Asphalt Mixtures. *Journal of Materials in Civil Engineering*, 25(9) (2013) 1344-1352. doi:10.1061/(ASCE)MT.1943-5533.0000664.
- [3]- A. Varveri, S. Avgerinopoulos, C. Kasbergen, A. Scarpas, A. Collop, Influence of Air Void Content on Moisture Damage Susceptibility of Asphalt Mixtures: Computational Study. *Transportation Research Record*, 2446(1) (2014) 8-16. doi:10.3141/2446-02.
- [4]- B. Killingsworth, Research results digest 291: Quality Characteristics for Use with Performance Related Specifications for Hot Mix Asphalt, TRB, National Research Council Washington, D.C. (2004).
- [5]- X. Luo, F. Gu, R.L. Lytton, Prediction of Field Aging Gradient in Asphalt Pavements. *Transportation Research Record*, 2507(1) (2015) 19-28. doi:10.3141/2507-03.
- [6]- Z. Leng, I.L. Al-Qadi, P. Shangguan, S. Son, Field Application of Ground-Penetrating Radar for Measurement of Asphalt Mixture Density: Case Study of Illinois Route 72 Overlay. *Transportation Research Record*, 2304(1) (2012) 133-141. doi:10.3141/2304-15.
- [7]- S.G. Williams, Non-nuclear Methods for HMA Density Measurements, MBTC 2075, Final Report. State Highway and Transportation Department, 2008.
- [8]- Z. Leng, I.L. Al-Qadi, S. Lahouar, Development and validation for in situ asphalt mixture density prediction models. *NDT & E International*, 44(4) (2011) 369-375. doi:10.1016/j.ndteint.2011.03.002.
- [9]- N.Q. Phuc, D.X. Truong, A study on using non-radioactive, non-destructive devices-troxler to control in-situ density of hot-mix asphalt. *Transport Journal*, (2018).
- [10]- IAEA, Manual on Nuclear Gauges. Incorporating: Applications Guide, Procedures Guide and Basics Guide,

International Atomic Energy Agency Vienna. (1996).

- [11]- A. Benedetto, L. Pajewski, Civil engineering applications of ground penetrating radar. Springer, 2015.
- [12]- A.P. Annan, Ground-Penetrating Radar, in Near-Surface Geophysics, D.K. Butler, Editor. Society of Exploration Geophysicists. (2005), 0. doi:10.1190/1.9781560801719.ch11.
- [13]- Y. Dong, F. Ansari, Non-destructive testing and evaluation (NDT/NDE) of civil structures rehabilitated using fiber reinforced polymer (FRP) composites, in Service Life Estimation and Extension of Civil Engineering Structures, V.M. Karbhari, L.S. Lee, Editors. Woodhead Publishing. (2011), 193-222. doi:10.1533/9780857090928.2.193.
- [14]- Z. Leng, I.L. Al-Qadi, An innovative method for measuring pavement dielectric constant using the extended CMP method with two air-coupled GPR systems. NDT & E International, 66 (2014) 90-98. doi:10.1016/j.ndteint.2014.05.002.
- [15]- S. Wang, X. Sui, Z. Leng, J. Jiang, G. Lu, Asphalt pavement density measurement using non-destructive testing methods: current practices, challenges, and future vision. Construction and Building Materials, 344 (2022) 128154. doi:10.1016/j.conbuildmat.2022.128154.
- [16]- T.E. Laboratories, Manual of Operation and Instruction - Model 2701-B PaveTracker™ Plus, Troxler Electronic Laboratories U.S.A. (2020).
- [17]- TCVN, 13348: 2021. Asphalt Mixtures –Test method for Density of Asphalt Mixtures In-place by the Electromagnetic Surface Contact Devices, Ministry of Science and Technology Vietnam. (2021).