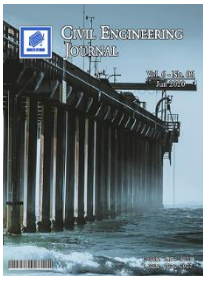
Available online at www.CivileJournal.org

# Civil Engineering Journal

Vol. 6, No. 6, June, 2020



# Efficacy of Non-nuclear Methods Used for Hot Mix Asphalt Density Determination

Shah Zaman [a], Muhammad Hassaan [b*], Jawad Hussain [a], Umar Hayat [c]

[a] *University of Engineering and Technology, Taxila, Pakistan.*

[b] *Shandong University , Jinan, China.*

[c] *University of Engineering and Technology, Lahore, Pakistan.*

Received 22 January 2020; Accepted 20 April 2020

**Abstract**

This paper presents research efforts with a major purpose of determining if electromagnetic, non-nuclear density gauges (NNDG) are competent enough for asphalt density measurement in comparison to the already existing standard core method (AASHTO T-166). Field, as well as laboratory studies, were conducted to assess the abilities of available non-nuclear devices as they need the appraisal for future use in many developing countries including Pakistan. NNDG data collected from 45 locations, compared to density determined in the laboratory for the cores extracted from the same location, shows that the results obtained from both the methods are comparable. Laboratory studies conducted on the slabs of open and dense gradations show that such an instrument performed well for dense gradation in comparison to open ones. The Calibration effect of the instrument has a valuable impact on the accurate density determination. Results indicated that such gauges are seriously affected by moisture presence on the surface of testing pavement. Moreover, the temperature dependency of non-nuclear gauges is among the major outcome of this research. Overall the performance of such gauges is valuable, and the results are comparable to the standard results of core methods. However, these results can only be used for Quality Assurance (Q.A) purposes and not for Quality Acceptance (Q.C) of the density of pavement.

*Keywords:* Hot Mix Asphalt; Non-nuclear Density Gauge; Core Method; Non-destructive Testing.

## 1. Introduction

Density of hot mix asphalt (HMA), because of many reasons, is of prime importance for those ample , increases deterioration in pavement structure and has possibility for oxidation to occur [1, 2], water damage [3-5] , raveling and cracking [6]. Asphalt density controls the in place air voids which should be greater than 3 percent to avoid premature rutting [7]. Since asphalt density brunt the air voids directly along with its impact on pavement durability thus raising the importance of density determination techniques. Moreover, accurate and rapid measurement of road density has also been the central focus of researchers across the world as road density is measured as a part of quality control by contractor while state or local agencies do it for quality assurance program.

Unlike many countries of the world, that has been using updated methods, and many modified equipment for asphalt density determination, traditional core method for this purpose is still being used by many developing countries including Pakistan. Core method that is carried out in accordance with American association of state highway and transportation officials (AASHTO) procedure AAHTO T-166 [8] disturbs the road integrity. Other

* Corresponding author: muhdhassaan93@gmail.com

http://dx.doi.org/10.28991/cej-2020-03091538

problems with Core method may include time restrictions to make the core sample air dried. Drying in oven at elevated temperature may result in distortion of core sample thereby disturbing the actual results [9].

Over the ensuring years, timely compaction results determination became the prime criteria for the paving industries. Nuclear density gauges were among earliest available non-destructive tool for density measurement. Such gauges work on emission and receiving back the scattered gamma rays [10]. These gauges were quite heavy in the past and operator use a scale to measure the density from a safe distance [11, 12]

Researchers have concluded that nuclear gauges are not as accurate as core method. On average density reading obtained from nuclear gauge were 10 kg/$m^3$ higher than that of core method. Moreover, nuclear density gauge data is highly operator dependent [13]. Nuclear density gauges delivered much to the paving industry but still there was a need for an instrument that was fast, non-destructive, being free from the restriction of licensing and radiations problem and more operator friendly [14]. Although a human body working around the nuclear density gauge receives 10-30 mR of radiations but these radiations can be much higher in case of not taking safety precautions seriously [15]. Radiation problem is associated with frequency of inspection and use of density gauges. However, these gauges are not a danger even after improper disposal [15].

In last decade, paving industry witnessed the revolution in density determination as industry witnessed non-nuclear density gauges. Operation of Non-Nuclear Density Gauge (NNDG) is based upon sending and receiving non-nuclear waves thereby overcoming the issues related to safety as in case of nuclear devices and destruction of pavement as for core method [16, 17].

This research work is the result of inspiration by the work of many researchers who have done admirable job until now to check the accuracy of many non-nuclear devices. One research conducted as pooled fund study concluded that density obtained by using PQI-300 was statistically different from core density in 68 percent of projects[17]. Overall PQI-300 reads the density values on the higher side. A research done in 2006 involved three different non-nuclear devices and their results were compared with nuclear method of density determination. The results suggested that non-nuclear gauges read density value lower than that of nuclear gauges [18].

One research suggested some factors including lab air voids, specific gravity and pavement layer thickness affected the gauge readings [19]. Other research concluded that orientation of the gauge, moisture presence and marking paint significantly change the gauge readings [20]. One of the research done on PQI suggests and recommends the device to be cost efficient and a better alternative to nuclear density gauges [21]. One research conducted on PQI-380 as non-nuclear asphalt density measuring technique stated that the number of cores drilled out from newly developed road can be reduced with the use of PQI-380 [11]. In a study of Rogge and Jackson [22] it is concluded that both the density gauges , nuclear as well as non-nuclear are not accurate enough to be comparable with core method. non-nuclear ,non-nuclear density gauges are said to be a standard equipment for asphalt density measurement only when they produce results comparable to AASHTO T 166 [23].

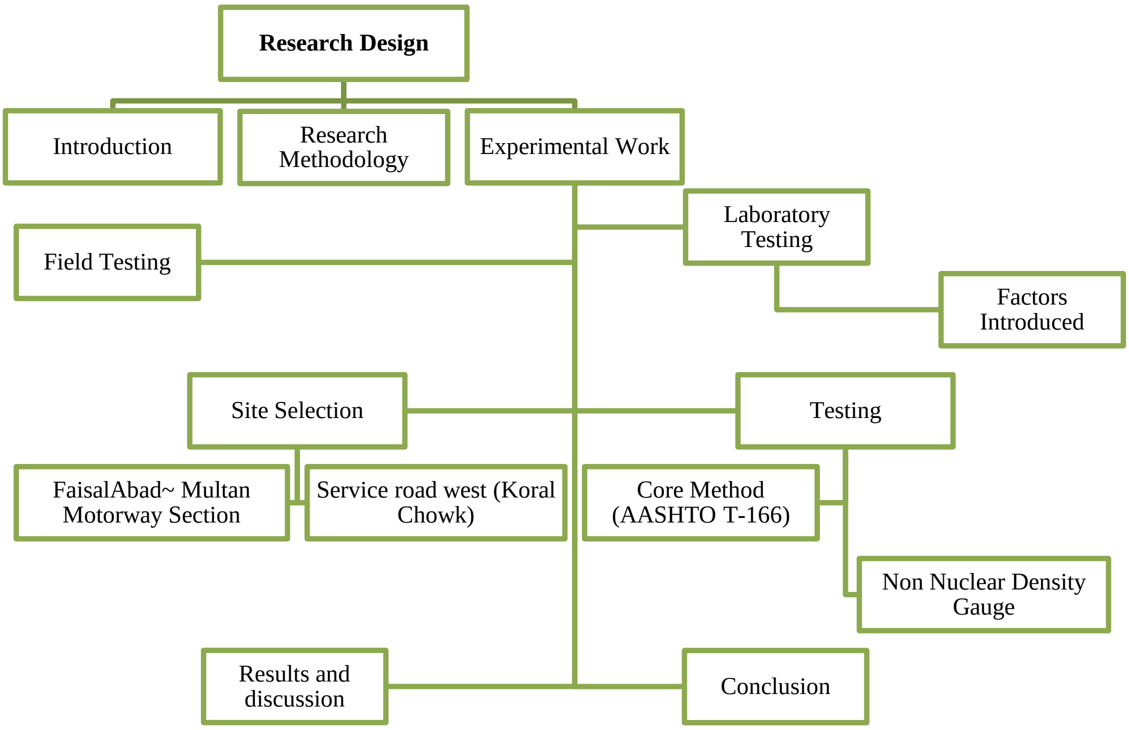
Motivation for this research work is primarily influenced by the fact that road infrastructure is on an emerging corner across many of the developing countries including Pakistan, making it essential to have better quality assurance equipment for road construction. Main objectives of the research include following:

- Checking the performance of non-nuclear density gauges for field conditions in comparison to traditional standard methods and establishing statistical correlation model for both the density data obtained from both the methods.
- Validation of non-nuclear density gauges in laboratory corresponding to various key factors that are more likely to affect the density measurement in field conditions.
- Establishing correlation for density measured through non-nuclear method and Saturated surface dry (SSD) method for various factors.

To accomplish and achieve these goals, Taxila institute of transportation engineering (TITE) step forward making it possible to have non-nuclear, non-nuclear asphalt density determination equipment that uses concept of impedance spectroscopy. This research is followed by section 2 of Research design which covers basics of electromagnetic density gauges and their operational principles. Under the section of research design materials that will be evaluated using such gauges are elaborated. General properties of bitumen along with the aggregate are enlisted in tabular and graphical form in this section. Section 3 covers the major results obtained from this research work. Under this section field results and the results obtained from laboratory assessment of non-nuclear methods are explained one by one. Laboratory results include the results of different factors introduced under controlled conditions that are more likely to affect the efficiency of the non-nuclear gauges under field conditions. Section 4 covers the major conclusions that are drawn based on the results obtained from both the field and laboratory evaluation of these methods.

## 2. Research Design

The experimental program was designed to achieve the stated objectives: to assess the precision of a non-destructive technique i.e. NNDG that is established and uses the non-nuclear method for HMA density measurement; and, to find the different factors affecting the performance of NNDG. In the first step, traditional destructive core method and NNDG were explained. Secondly, Cores were extracted from the locations where NNDG tests were performed and their density was tested in laboratory to compare the results with densities obtained from NNDG. As it is not enough to check the apparent density while doing quality control, One should also check the compaction temperature along with other mechanical properties and factors affecting density [24]. Therefore, second step included samples preparation in the laboratory to test the various factors i.e., moisture, temperature, gradation, paint and construction debris. Flow chart for the research methodology is sown below:




**Scheme 1. Schematic diagram and actual non-nuclear density gauge**

In this section, the detail specifications of non-nuclear density gauges commonly available are discussed and the specifications of equipment that has been used in this research are compared to the commonly used devices. The area selected for the sampling is introduced and field testing is discussed along with core extraction to compare NNDG performance in the field. Further the materials characterization, sample preparation, testing methods of various factors affecting the NNDG performance in laboratory-controlled conditions is discussed.

### 2.1. Non-destructive Technique for HMA Density Measurement

Traditional way of HMA density measurement involves cores extractions thereby associated with the issues of damaging the pavement structure and integrity. To overcome this issue of pavement damage, a non-destructive technique has been established that determines the pavement density even without extracting the cores. Basic principle utilized by non-nuclear density gauges (EMDG) are explained below:

#### 2.1.1. Operation Principles of EMDG

Non-nuclear density gauges, also known as non-nuclear density gauges, are those which involves non-nuclear waves in order to determine the in-situ density of asphalt pavement. Basic principle behind majority of the non-nuclear asphalt density gauge is based on measuring asphalt density by receiving the scattered non-nuclear rays imparted upon pavement surface. It has been reported in the literature that non-nuclear density gauges utilize the concept of impedance spectroscopy to measure electric response of asphalt, from which density can be calculated.

Figure 1 explains the schematic of operation principle of non-nuclear density gauges i.e. Pavement quality indicator (PQI) where it contains a transmitter from which the rays are imparted on the pavement surface and other is receiver that receives the rays scattered after hitting the surface.

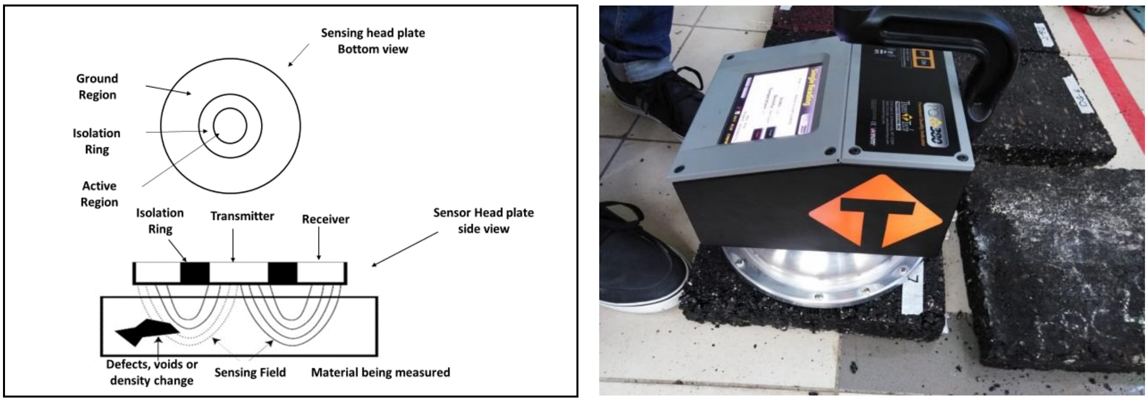



**Figure 1. Schematic diagram and actual non-nuclear density gauge**

Pavement quality indicator works on constant voltage, low frequency, electrical impedance approach based on toroidal electrical sensing field. Impedance spectroscopy is determination of material's dielectric properties based on interaction of external field with the electric dipole moment of substance under test (SUT), for a known frequency range. Placing a non-conductor i.e. dielectric reduces the strength of this electrical sensing field. The amount by which electric field is reduced due to presence of non-conductor is referred to as dielectric response of material. Density estimation of asphalt mat is carried out based on the electrical field response from the surface displayed on the screen. Since HMA comprises of aggregates, binder, air voids and to some extent moisture. Thus, density of HMA measured using non-nuclear density gauges highly depend upon the dielectric constant of all these constituents. As dielectric constant for all these constituents varies considerably (e.g. air, 1; water, 80; aggregate, 4-20) [25].

Such instruments have the capability of eliminating the issues related with core extraction along with completely bypassing the licensing, and health issues that are related to nuclear density gauges. Fundamentals of NNDG are enlisted in Table 1.

**Table 1. General specifications of NNDG**

| | |
|---|---|
| **Sensing area** | 11 inches (27.9 mm) diameter base plate ensures the accurate measurement for fine as well as coarse surface. |
| **Measurement depth** | NNDG measures density for a depth range of 1-4 inches |
| **temperature range** | density can be accurately measured for a temperature range of 0-350˚F |
| **Measurement technique** | bombardment of electromagnetic rays |

## 2.2. Tests for Evaluating NNDG Performance

This section explains the testing carried out for the research purpose. Firstly, sites selected for field evaluation of NNDG are discussed. Further basic information regarding the pavement material of the selected sites is also described. Secondly laboratory evaluation of the instrument performance against various factors is explained. Different level of various factors introduced is explained in detail. Field studies were conducted to evaluate non-nuclear density gauge in comparison with core method. It included total of 45 cores extracted from two different sites. One of the sites was Faisalabad Multan motorway M-4 where asphalt overlay was done from 27+000-52+000 kms. The cores extracted were comprised of asphalt wearing open involving aggregate gradation as per NHA-B. Google map image is inserted for the first site as shown in Figure 2(a); while other site was a service road in Rawalpindi Koral chowk. Total of fifteen cores were extracted from this site. This road was also constructed using NHA-B gradation and cores were extracted for wearing coarse. Google map image for this site is inserted as shown in Figure 2(b).

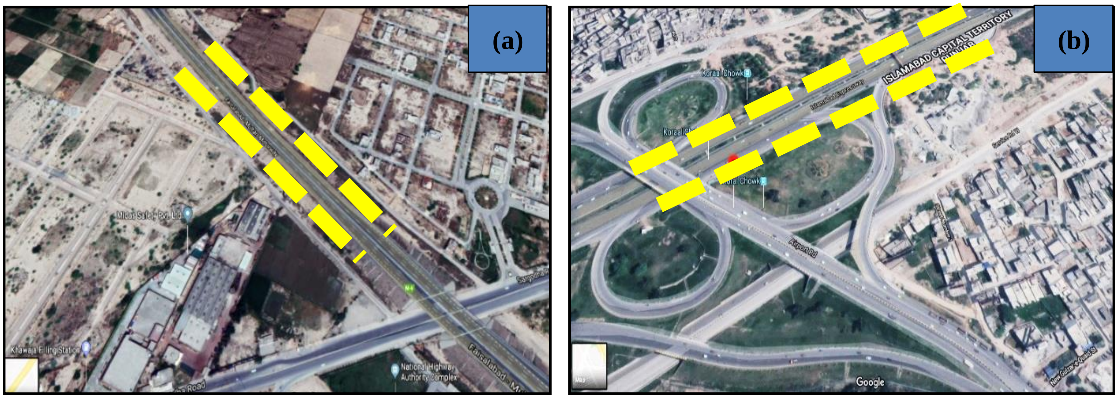



**Figure 1. Google map images for selected sites: (a) Faisalabad-Multan motorway; (b) Koral chowk**

To check the impact of different factor, total of thirty slabs were prepared; fifteen slabs for each gradation i.e. NHA-A as well as NHA-B. Firstly, NNDG readings were compared to density reading measured by using laboratory saturated surface dry (SSD) method. This was carried out to evaluate EM density Gauge for both NHA-A as well as NHA-B in general. Further it covered EM density gauge data controlled by many factors for slabs prepared from both gradations. Measurement condition investigated in the laboratory study for better assessment of the instrument is shown in Table 2 of factors and levels.

**Table 1. Factors and level table**

| | Factors | | Level |
|---|---|---|---|
| EM density gauge | Calibration Method | 1 | Linear offset method |
| | | 1 | 5˚Celcius |
| | | 2 | 15˚Celcius |
| | Temperature | 3 | 30˚Celcius |
| Environmental conditions | | 4 | 40˚Celcius |
| | | 1 | 0.05 g/cm$^2$ |
| | Moisture | 2 | 0.1 g/cm$^2$ |
| | | 3 | 0.15 g/cm$^2$ |
| Slab material | Gradation | 1 | Open gradation (NHA-A) |
| | | 2 | Dense gradation (NHA-B) |

## 2.3. Materials for Laboratory Work

Material used in the slab preparation for the performance evaluation of NNDG against various factors is discussed in this section. Dimensional characteristics of prepared slabs along with properties of various materials used are also explained and discussed in the coming lines. Total of thirty slabs were prepared, 15 for each gradation. Dimensionally Slabs were 12” × 12” with thickness of 2”. Slabs were compacted using roller compactor with thirty passes for each slab. Two types of commonly available gradations i.e. NHA-A and NHA-B were used for slab preparation. Gradation curve for NHA-A and NHA-B are shown in Figure 3.

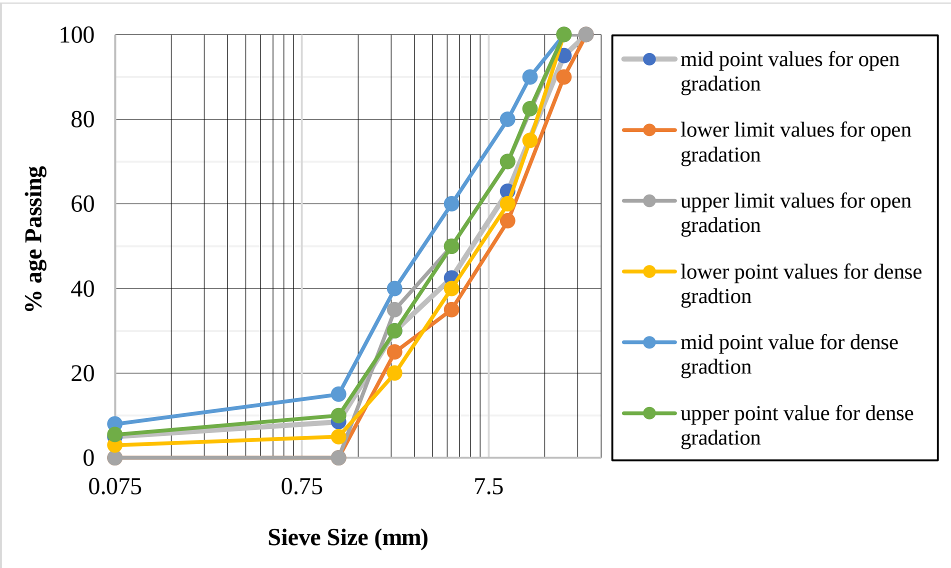



**Figure 2. Gradation curves for both gradations e.g. open and dense**

For both gradations i.e. NHA-A and NHA-B, mid values were used in selecting aggregates for slab preparation. Source of aggregate used in the slab was Margalla. Bitumen used for slab preparation was obtained from attock oil refinery with penetration grade of 60/70. Marshal asphalt mixture deign method was used to determine the optimum binder content for both the gradation.

# 3. Results and Discussion

Major outcomes from the research work supporting the stated objectives are described in this section. At first, the results obtained from field studies carried out to make correlation between the cores and NNDG densities are discussed. Secondly, results obtained from laboratory studies which were aimed to take the effect of different factors on NNDG reading into consideration is elaborated. Correction factors developed to correlate the gauge density with saturated surface dry density (SSD) are also discussed one by one. In coming paragraphs all these results are explained and elaborated thoroughly.

### 3.1. Correlating Core and NNDG densities

Field studies included two sites where density data was obtained during high temperature and low temperature conditions. One site was a newly overlaid waring course prepared as per NHA-B gradation on M-4 (Pindi-Bhattyan). The average temperature during the study ranged from 25 to 45˚C. From this site density data for the thirty cores was obtained and compared to the data obtained from EM density gauge data. Second site selected was the service road west located near Koral-chowk interchange, Rawalpindi during winter when temperature ranged from 5 to 25˚C. This road also has the gradation as per NHA-B classification. Total of 15 cores were extracted from this site.

From the correlation coefficient it is obvious that the NNDG performance is satisfactorily well for both the sites under both extreme temperature condition. It is shown in Figure 4 that for the first site where temperature conditions were extremely high, the correlation coefficient is 0.82. This means that 82 percent variance in the density measured by core method can be explained collectively by the NNDG data. Similarly, Figure 5 shows the same trend for the second site where temperature conditions were at the lower end. Correlation coefficient for this site is 0.84 which means 84 percent variance in the core density can be accurately and collectively explained by the density data of NNDG.

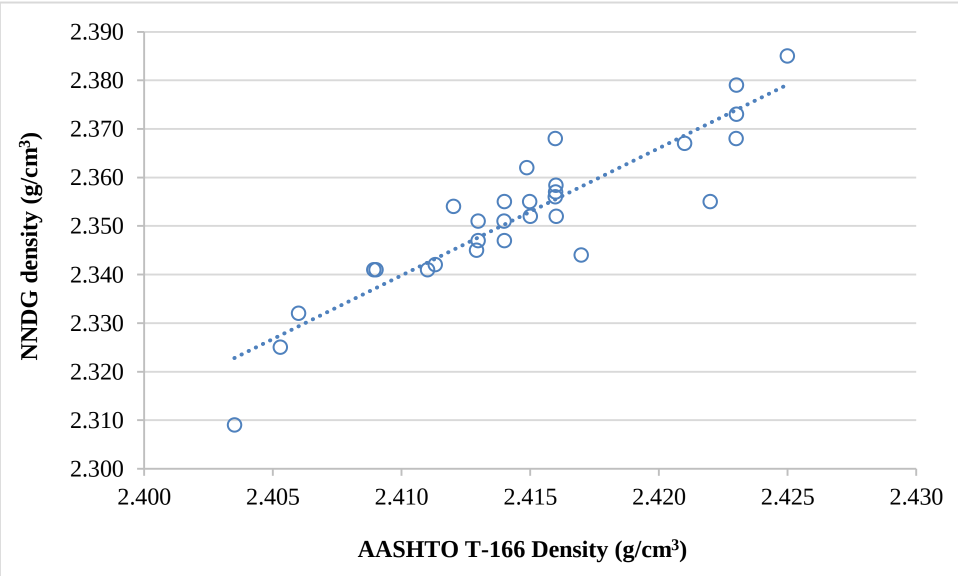



**Figure 3. Correlation coefficient and line of equality for both the sites: M-4**

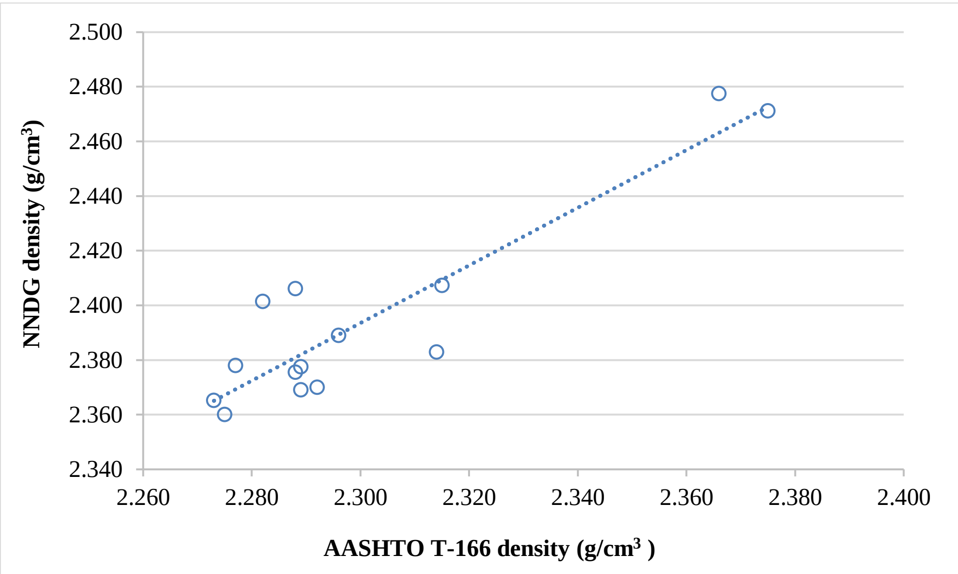



**Figure 4. Correlation coefficient and line of equality for both the sites: Koral Chowk**

Error measurement for the model is of prime importance and most important error measuring tool is root mean square error (RMSE) as it bypass the absolute value that is undesirable in many of the cases [26]. But at the same time mean absolute error (MAE) is natural way of measuring error being less ambiguous than RMSE [27] therefore we took both the errors for our data set. For our dataset both the values of error are smaller confirming the validity and accuracy of the results.

Since temperature for both the sites selected differed significantly thus the NNDG data has shown considerable variations for both the sites. For site 1 (Pindi-Bhatyan) where temperature was high non-nuclear density gauge read the density reading lower in comparison to core method. On average NNDG readings were 0.06 g/cm$^3$ lower than that of core results. For site 2 (Koral Chowk) where temperature was at lower side NNDG read the density value 0.10 g/cm$^3$ higher than that of core density readings.

The statistical product and solution services (SPSS) version 21 was used to develop the equations for field results. Equation 1 developed can be used to predict the core density from the data obtained from NNDG for asphalt wearing coarse for lower temperature (5 to 25˚C) while Equation 2 can be a prediction tool in case of high temperature (25 to 40˚C) conditions for asphalt wearing coarse.

$$DCore = 0.949 \times DNNDG + 0.027 \tag{1}$$

$$DCORE = 0.381 \times DNNDG + 1.516 \tag{2}$$

Where:

$D_{NNDG}$ = density measured using non-nuclear density gauge, g/cm$^3$

$D_{CORE}$ = Density of the same point determined using core method, g/cm$^3$

These equations are only valid for dense gradation asphalt for varying temperature and correlation for open gradation are developed in laboratory study as no such pavement with NHA-A gradation is available in the vicinity of study area. Moreover, for open gradation with other prevailing conditions relationship are also developed in the laboratory studies.

### 3.2. Factors Affecting NNDG Performance

Evaluation of the gauge in controlled settings of laboratory is also necessary for thorough investigation of different factors that may disturb the actual readings of NNDG. Therefore, instrument validity was checked and analyzed against different parameters sequentially discussed along with the correction factors for each of the parameter in the coming lines.

#### 3.2.1. Calibration Method

Calibration of any Non-nuclear density gauge is an important tool to increase accuracy in the results. Mix calibration as well as linear offset calibration method may be adopted for any of the NNDG. This research adopted linear offset method after calibrating the instrument for respective mix. For both the gradations, five slabs for each were prepared to determine the linear offset value. Offset was determined by measuring density of the slabs using NNDG and the results were compared to density determined using saturated surface dry (SSD) method using ASTM D2726.

Results for the calibration show that NNDG reads higher density value for both mixes. For NHA-A, this value was 0.15 g/cm$^3$ while for NHA-B instrument read 0.20 g/cm$^3$ higher. These values were then used to get calibrated data of the slabs from raw data by subtracting the offset

Density data obtained by density gauge in comparison to lab density, for NHA-A percentage difference of 7.8 for un-calibrated or raw data was reduced to only 1.9 using linear offset calibration method Similarly, for NHA-B, percentage difference in readings were reduced to 2.761 from 7.00 as shown in the same figure.

Box plots drawn using SPSS are drawn so that we can compare the results of calibrated and un-calibrated NNDG data with laboratory measured density. It is obvious from the graphs that for both the gradation median for calibrated data is less separated from the median of laboratory density in comparison to un-calibrated data for which medians are well separated when compared to laboratory density data box plot.

Density distribution for calibrated data is more symmetric across its median in case of NHA-A as shown in Figure 6 which means 50 percent of the values fall below the median while 50 percent are more than that of median. For NHA-B plot is skewed right as shown in Figure 7 that means that more values are distributed below the median.

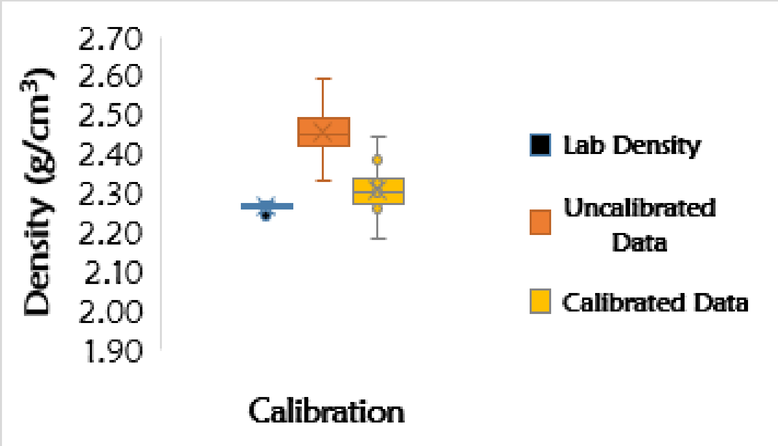



**Figure 5. Box plot illustration for calibrated and un-calibrated densities: NHA-A**

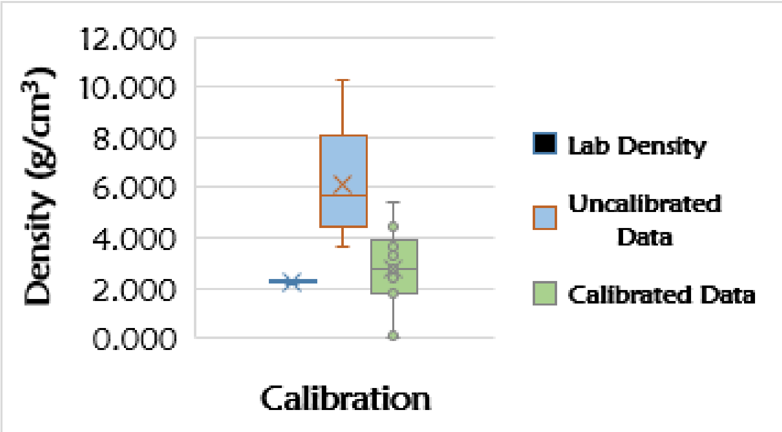



**Figure 6. Box plot illustration for calibrated and un-calibrated densities: NHA-B**

Similarly, boxplot for calibrated data of NHA-B is large in comparison to that for NHA-A which means more variability is there in case of NHA-B. After the results are obtained and analyzed, this study highly recommends using the calibrated data as per linear offset method along with mix calibration technique to achieve better accuracy and correlation to that of density values determined using standard method. A similar study conducted by Rao et l. (2007) [18] states that non-nuclear density gauge can be used for in-situ density measurement of flexible pavement. However, study suggests that an appropriate calibration technique is must adopted in order to get better and relatable results in comparison to that of already existing standard core method of density measurement.

### 3.2.2. Moisture Condition

Density measurement in presence of moisture, even in a very less amount with no visible marks on the pavement surface, may affect the accuracy of non-nuclear density gauge. This moisture, if present in high quantity can change the density reading drastically determined through such gauges [25, 28] as dielectric constant for water is much higher than that of asphalt mix whose value lies between 4 and 7 [29]. Dielectric constant for a HMA material increases with an increase in moisture [30]. Therefore, it is necessary to validate and check the accuracy of instrument in the presence of moisture.

To scrutinize the relationship between the moisture and NNDG data, water was sprayed manually in different rates titled as moisture level 1 (ML1), moisture level 2 (ML2) and moisture level 3 (ML3) having 0.05, 0.1 and 0.15 g/cm$^2$ of water sprayed respectively for slabs prepared from both the gradations as air voids variation may also impact the dielectric constant of HMA mat [31].

For water sprinkled at the rate of ML1, no significant water accumulation can be seen, and the slabs were just wet. While for further increase at ML2of water sprinkle water went on accumulating on some points on the slabs. When ML3 of water was introduced, physical presence of water can be observed on larger portion of the slab surface. Water accumulation for different spraying rates is shown in Figure 8.

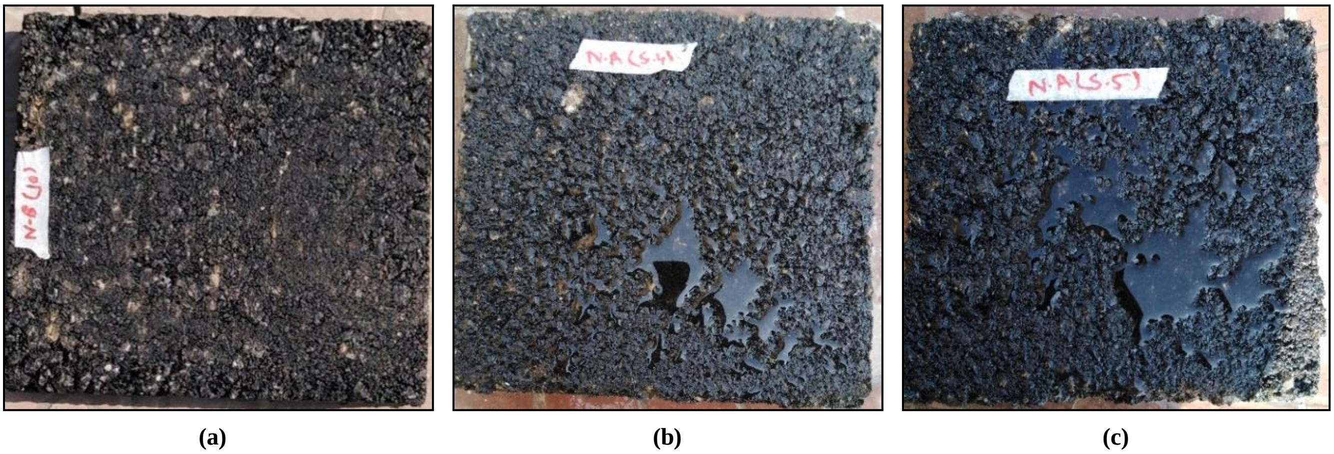



**Figure 7. Water sprayed manually on the test slabs: (a) ML1; (b) ML2; (c) ML3**

For dense gradation of asphalt mix slabs, density reading first increases for the water sprinkled at the rate of ML1 in comparison with air dried slabs. While further increase of water has shown the trend for gradual decrease in density reading. On average for ten slabs density reading were 2.517 g/cm$^3$ when water was sprinkled at the rate of ML1 in comparison to density reading of 2.415 g/cm$^3$ when the slab was dry. While further increase in moisture level gradual decrease the density value.

For water sprinkled at the rate of ML2 density value decreased to 2.503 and at final stage density value further decreased to a value of 2.499 for water sprinkled at the rate of ML3. A bar chart shown in Figure 9 shows the average density readings for different moisture level in comparison to lab density measured by saturated surface dry (SSD) method. Overall best comparison of the density readings with that of standard method can be made when the slabs were air dried with percentage difference of 16.2 while maximum percentage difference of the reading is 24.2 from three of the water sprinkled level.

Similarly, for slabs with open gradation prepared in accordance with NHA-A density gauge reading kept on increasing till ML2 of sprinkled water. Figure shows that average density value of ten slabs for dry condition was 2.43 g/cm$^3$ which keep on increasing till the value of 2.56 g/cm$^3$ for sprinkle rate of 0.1 g/cm$^2$ while further sprinkle of water slightly decreases the value to 2.54 g/cm$^3$ as shown in Figure 10.

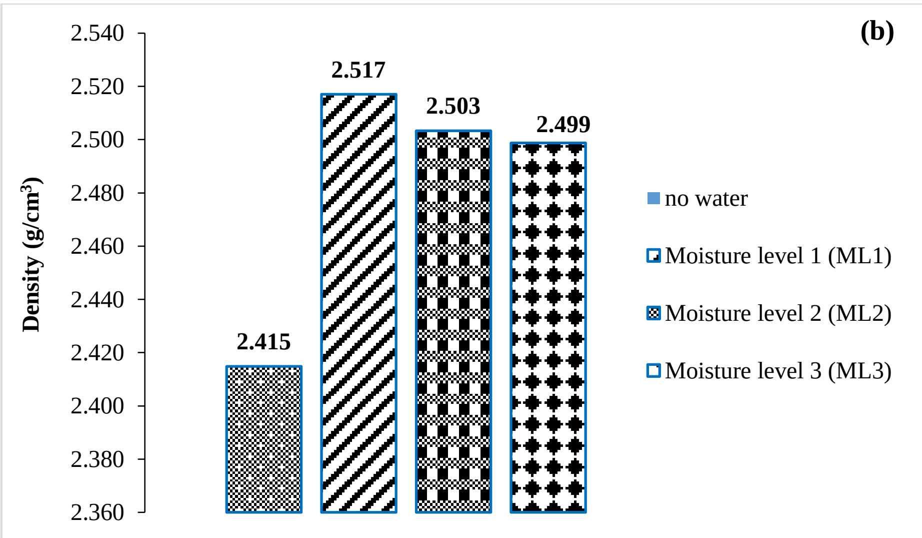



**Figure 8. Variation in density for different moisture level (b) NHA-B**

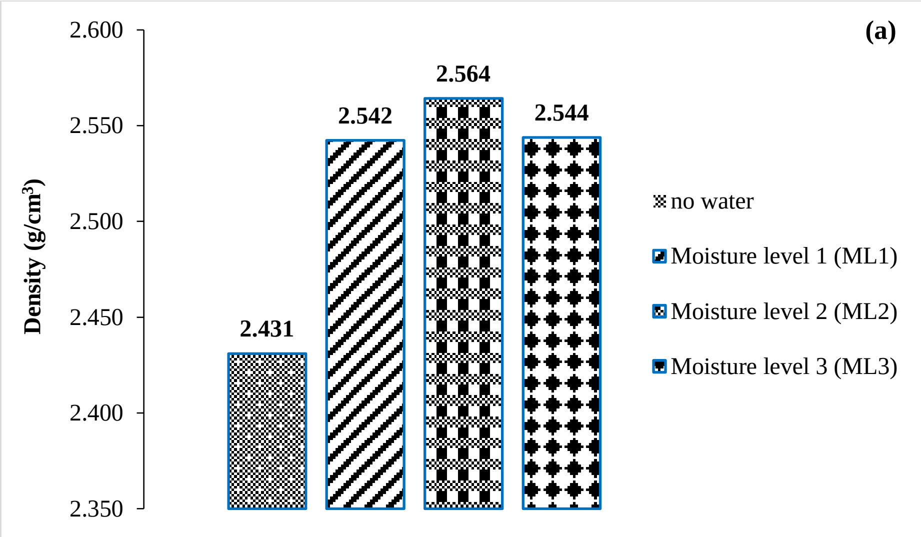



**Figure 9. Variation in density for different moisture level: (a) NHA-A**

The probable reason for density increases in case of NHA-B for water sprinkle at the rate of ML1 can be the moistures that fills the voids initially and increasing the overall dielectric constant of asphalt mix thereby increasing density measured using NNDG as explained in Figure 11. While further increase in moisture has made the density reading to decrease a very little.

Similarly increase in density reading till ML2 of water sprinkled for NHA-A can be justified, as NHA-A classification carry more air voids therefore water kept on accumulating and filling the air voids present in the slab thereby increasing overall dielectric constant of HMA slabs. Therefore, density readings were increase in comparison to increasing dielectric constant. While introducing more water to the slab no significant change in the density reading was observed.

These results are verified by a study conducted by Leyland and Maharaj (2010) [30] that concludes that dielectric constant of material increase linearly wit increase in moisture content present on that material. This study supports our results as density determined using non-nuclear density gauge is on an increasing trend as moisture content increases.

### 3.2.3. Temperature condition

Temperature variation is ungovernable phenomena while density determination as road construction may start at any time of the year. Moreover, temperature variation from one place to other cannot be controlled. Temperature dependency for the dielectric constant of material and hence the gauge reading, has already been affirmed. Different material may exhibit different rate of change in dielectric constant for same temperature variation [30]. Researchers concluded that the temperature may have an impact on electrical conductivity of asphalt concrete [25]. That's why it is obvious that the density readings taken for the same material of asphalt may be affected by taking measurement at different temperature as well as at the same temperature for different mix of asphalt.

This research tried to accomplish the effect of temperature on non-nuclear density gauge reading. For this purpose, slabs prepared with both open as well as dense gradations as per NHA-A and NHA-B respectively were checked for temperature variation. Temperature was raised from 5˚C to 40˚C including measurement at 15˚C and 30˚C for both type of slabs and the results were compared to the density reading of slabs measured in laboratory using ASTM D2726 [32]. This temperature range is selected as this study has a scope of comparing the actual field temperature conditions with that of lab studies. However, for future this temperature range could be increased to make a real time temperature effect on the density determined using NNDG.

For slabs prepared as open gradation in accordance with NHA-A observed the value of 2.470 g/cm$^3$ at 40˚C which decreased to the value of 2.376 g/cm$^3$ at 5˚C of temperature as illustrated in bar chart presented in Figure 11 While for slabs prepared with dense gradation i.e. NHA-B density measured at 40˚C was 2.511 g/cm$^3$ that keep on decreasing as temperature was raised ending at the value of 2.378 g/cm$^3$ at 5˚C as shown in Figure 12.

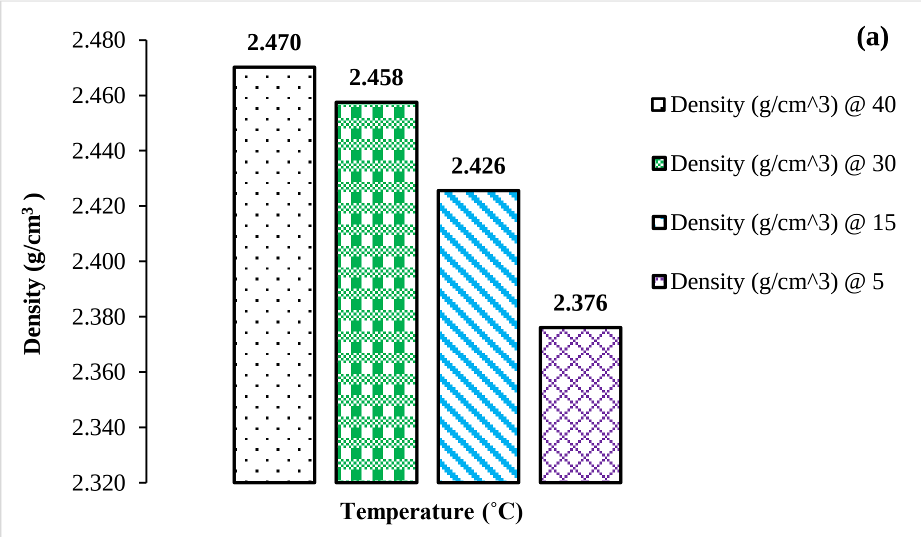



**Figure 10. Variation in gauge reading for various temperature: NHA-A**

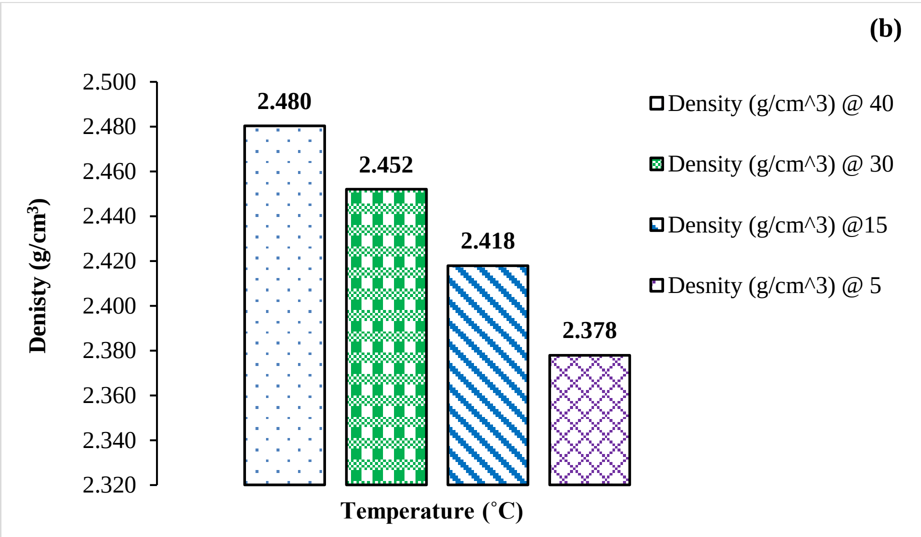



**Figure 11. Variation in gauge reading for various temperature: NHA-B**

This phenomenon of increasing density with temperature increase can be understood by the permittivity dependence on temperature for asphalt pavement. Density of asphalt is directly proportional to permittivity that highly depends upon the temperature variation in asphalt [33]. It has been verified from researches that for asphalt samples permittivity increases with increasing temperature thereby density will be increased with the temperature increment.

Moreover, dielectric constant has also a linear relation with the temperature [30]. Thus, temperature increase caused the dielectric constant value to rise which in return results in higher density values measured by NNDG

In case of NHA-A, an average percentage difference in density reading decreased from 7 at 5˚C to 3.1 at 40˚C when compared with laboratory measured density according to SSD method while this percentage difference in case of NHA-B slabs decreased from 9.17 to 5.2. For both the gradations we have observed an increasing trend of density determined using NNDG with increasing temperature of the pavement surface. This trend of density can be verified by a study conducted to check the trend of dielectric constant of various materials against temperature variations [30]. Study concludes that for hot mix asphalt dielectric constant increases with increases temperature. Therefore, density measured through NNDG has an increasing trend against increasing surface temperature of pavement.

### 3.2.4. Analysis of Variance

Impact of various factors argued previously is also investigated in an offbeat perspective- the analysis of variance (ANOVA). Statistical product and solution services (SPSS) was used to perform one-way ANOVA to see the effect of different levels of calibration, moisture, temperature, paint and sand for both the gradations. The result of ANOVA is tabulated in Table 3.

**Table 2. Summary of Analysis of Variance (ANOVA)**

| Gradation | Factors | P-value |
|---|---|---|
| **Open gradation (NHA-A)** | Low temperature (≤5˚C) | 0.0000 |
| | Medium temperature (≤30˚C) | 0.00000 |
| | High temperature (≥40˚C) | 0.000004 |
| | Moisture level 1 (0.05 g/cm$^2$) | 0.000002<br>0.000<br>0.000 |
| | Moisture level 2 (0.10 g/cm$^2$) | 0.00000 |
| | Moisture level 3 (0.15 g/cm$^2$) | 0.000002 |
| | uncalibrated data | 0.000 |
| | Calibrated data (linear offset) | 0.094 |
| **Dense gradation (NHA-B)** | Low temperature (≤5˚C) | 0.0000 |
| | Medium temperature (≤30˚C) | 0.0000 |
| | High temperature (≥40˚C) | 0.000005 |
| | Moisture level 1 (0.05 g/cm$^2$) | 0.000005 |
| | Moisture level 2 (0.10 g/cm$^2$) | 0.000048 |
| | Moisture level 3 (0.15 g/cm$^2$) | 0.000102 |
| | uncalibrated data | 0.000 |
| | Calibrated data (linear offset) | 0.089 |
| | Calibrated data (linear offset) | 0.089 |

The P-values in table determine the probability whether the factor means are different on predefined risk level. The risk level chosen for analysis was 0.05. For any factor, the mean value less than 0.05 indicate convincing difference and hence the effect of factor being significant

P-values enlisted in the above table confirms that for both the gradations temperature variation is obvious while instrument also changes the reading in the presence of very small amount of water. ANOVA confirms that calibration of the instrument produces more consistent results. While sand and paint presence on the pavement surface do not have any significant impact on the gauge reading.

## 4. Conclusions

This research validated the precision and accuracy of non-nuclear density gauges in uncontrolled field conditions along with controlled laboratory conditions. This research work was limited to one type of non-nuclear density gauge. Efficiency of such instruments were validated in comparison to a standard method of density determination. The major findings of the research are synopsized as follow:

- Field study supported the instrument capability for density determination for the pavement made up of dense gradation for low as well as high temperature conditions as maximum percentage difference of 3.9 is observed. However, uncertainty present in data and unexpected variations in the results obtained by the density gauge, we can quote the value as a reference only if it is comparable to standard value measured as per AASHTO T-166. Field study cannot support the measurement of asphalt density solely by the gauge;
- Laboratory study suggests the linear offset calibration must be accomplished prior to density measurement using gauge as it is clear from the results that it significantly impacts the density readings;
- Statistical analysis has shown that the impact of gradation on gauge density cannot be neglected. Coefficient of variance for open gradation of asphalt pavement i.e. NHA-A is on lower side as compare to NHA-B i.e. dense gradation giving us the idea of better gauge performance with open gradation pavement;
- Although manufacturer literature emphasizes insensitivity of the instrument to the presence of moisture. However, results go contrary to the statement as density readings were being affected by the presence of moisture even in the situation when the surface is just wet. Therefore, this study suggests taking measurement only if the surface of the pavement is completely dry for better results and better accuracy;
- Results indicates that effect of temperature variation cannot be ignored as density continuously kept on decreasing as the temperature is raised for both of gradation.

### 4.1. Future Aspects of the Research

Overall performance of NNDG can be reported as satisfactory. But more of the research must be carried out in order to determine the possible effect of layer thickness, asphalt binder content and other factors that are ungovernable during field measurement of the density using the non-nuclear density gauges. Author suggest getting the optimum value of temperature for which instrument readings have best correlation with that of measured using standard method. Moreover, massive research potential in this field is still present if density determination techniques are validated on the basis of different aggregate and bituminous materials.

## 5. Acknowledgements

Authors Acknowledge national highway authority of Pakistan, for paving a smooth way in determining the density data using non-nuclear density gauges.

## 6. Conflicts of Interest

The authors declare no conflict of interest.

## 7. References

[1] Kandhal, Prithvi S., and Sanjoy Chakraborty. “Effect of Asphalt Film Thickness on Short- and Long-Term Aging of Asphalt Paving Mixtures.” Transportation Research Record: Journal of the Transportation Research Board 1535, no. 1 (January 1996): 83–90. doi:10.1177/0361198196153500111.

[2] Caro, Silvia, Eyad Masad, Amit Bhasin, and Dallas Little. “Micromechanical Modeling of the Influence of Material Properties on Moisture-Induced Damage in Asphalt Mixtures.” Construction and Building Materials 24, no. 7 (July 2010): 1184–1192. doi:10.1016/j.conbuildmat.2009.12.022.

[3] Lee, Chanho, Jung-Sik Kim, Hyungsoon Shin, Young-June Park, and Hong-Shick Min. “A New Hole Mobility Model for Hydrodynamic Simulation.” Microelectronics Reliability 40, no. 12 (December 2000): 2019–2022. doi:10.1016/s0026-2714(00)00094-9.

[4] Varveri, A., S. Avgerinopoulos, C. Kasbergen, A. Scarpas, and A. Collop. “Influence of Air Void Content on Moisture Damage Susceptibility of Asphalt Mixtures.” Transportation Research Record: Journal of the Transportation Research Board 2446, no. 1 (January 2014): 8–16. doi:10.3141/2446-02.

[5] Xu, Siyuan, Feipeng Xiao, Serji Amirkhanian, and Dharamveer Singh. “Moisture Characteristics of Mixtures with Warm Mix Asphalt Technologies – A Review.” Construction and Building Materials 142 (July 2017): 148–161. doi:10.1016/j.conbuildmat.2017.03.069.

[6] Luo, Xue, Fan Gu, and Robert L. Lytton. “Prediction of Field Aging Gradient in Asphalt Pavements.” Transportation Research Record: Journal of the Transportation Research Board 2507, no. 1 (January 2015): 19–28. doi:10.3141/2507-03.

[7] Brown, E. Ray, and Stephen A. Cross. “Comparison of laboratory and field density of asphalt mixtures.” National Center for Asphalt Technology (US), (1991). doi:10.21949/1404493.

[8] Association American of State Highways and Transportaion Officials standards, “AASHTO standards.” Part 2A Tests, Twenty eight, 2008, p. 1059.

[9] Chevrou, R. B. "La loi tronquée de de Liocourt." In Annales des sciences forestières, 47, no. 3. EDP Sciences, (1990): 229-239. doi:10.1051/forest:19900304.

[10] Smith, Bryan C., and Brian K. Diefenderfer. “Comparison of Nuclear and Nonnuclear Pavement Density Testing Devices.” Transportation Research Record: Journal of the Transportation Research Board 2081, no. 1 (January 2008): 121–129. doi:10.3141/2081-13.

[11] Van den bergh, Wim, Cedric Vuye, Patricia Kara, Karolien Couscheir, Johan Blom, and Philippe Van Bouwel. “The Use of a Non-Nuclear Density Gauge for Monitoring the Compaction Process of Asphalt Pavement.” IOP Conference Series: Materials Science and Engineering 236 (September 2017): 012014. doi:10.1088/1757-899x/236/1/012014.

[12] Padlo, Patrycja, Lisa Aultman-Hall, and Nikiforos Stamatiadis. “Passengers and Other Factors Affecting the Safety of Young and Older Drivers.” Transportation Research Record: Journal of the Transportation Research Board 1937, no. 1 (January 2005): 7–13. doi:10.1177/0361198105193700102.

[13] Jadhav, S. V., and K. V. Marathe. “Micellar Enhanced Ultrafiltration: A Comparative Study.” The Canadian Journal of Chemical Engineering 91, no. 2 (December 19, 2011): 311–317. doi:10.1002/cjce.21613.

[14] Sully-Miller Contraction, C. O. "A Summary of Operational Differences between Nuclear and Non-nuclear Density Measuring Instruments 5." (October 2000): 1-5.

[15] Korn, James H. “Myth Busters.” Edited by Danny Wedding. PsycCRITIQUES 55, no. 3 (2010). doi:10.1037/a0018442.

[16] T. Systems, “Pavement Quality Indicator TM Model 301 Operator’s Handbook,” Quality, pp. 1–36.

[17] Romero, Pedro. "Evaluation of non-nuclear gauges to measure density of hot-mix asphalt pavements." Pooled Fund Study Final Report, the University of Utah, Department of Civil and Environmental Engineering (2002).

[18] Rao, Chetana, Harold Von Quintus, and Robert L. Schmitt. “Calibration of Nonnuclear Density Gauge Data for Accurate In-Place Density Prediction.” Transportation Research Record: Journal of the Transportation Research Board 2040, no. 1 (January 2007): 123–136. doi:10.3141/2040-14.

[19] Von Quintus, Harold L., Robert Schmitt, and Chetana Rao. “Non-nuclear density testing devices and systems to evaluate in-place asphalt pavement density.” Wisconsin Highway Research Program, (May 2006).

[20] Williams, Stacy G. “Non-nuclear methods for HMA density measurements: final report, June 2008.” No. MBTC 2075. University of Arkansas, Fayetteville. Dept. of Civil Engineering, (2008).

[21] Z. Zhuang and Y. K. Cho, “Non-Nuclear Method for HMA density measurements Non-Nuclear Method for HMA density measurements,” no. December, (2017).

[22] Rogge, David F., and Michael Adam Jackson. “Compaction and measurement of field density for Oregon open-graded (F-Mix) asphalt pavement.” No. FHWA-OR-RD-99-26. (1999).

[23] Z. Zhuang, “Effectiveness study of Non-Nuclear Gauge for Hot Mix Asphalt (HMA) Pavement Construction,” (2011).

[24] Vasenev, Alexandr, Frank Bijleveld, Timo Hartmann, and André G. Dorée. "A real-time system for prediction cooling within the asphalt layer to support rolling operations." In Euroasphalt and Eurobitume Congress, (2012).

[25] Sargand, Shad M., Sang-Soo Kim, and Stephen P. Farrington. "Non-nuclear density gauge comparative study." Draft Final Report. Ohio Research Institute for Transportation and the Environment 114 (2005): 45701-2979.

[26] Chai, T., and R. R. Draxler. “Root Mean Square Error (RMSE) or Mean Absolute Error (MAE)? – Arguments Against Avoiding RMSE in the Literature.” Geoscientific Model Development 7, no. 3 (June 30, 2014): 1247–1250. doi:10.5194/gmd-7-1247-2014.

[27] Willmott, CJ, and K Matsuura. “Advantages of the Mean Absolute Error (MAE) over the Root Mean Square Error (RMSE) in Assessing Average Model Performance.” Climate Research 30 (2005): 79–82. doi:10.3354/cr030079.

[28] Wen, Haifang, Sunil Sharma, Mark Rose, Jingan Wang, Anthony Timm, and Mary Brown. “Review of Non-Nuclear Density Gauges as Possible Replacements for ITD’s Nuclear Density Gauges.” No. FHWA-ID-15-210. Idaho. Transportation Department, (2015).

[29] Leng, Zhen, Zeyu Zhang, Yuan Zhang, Yangyang Wang, Huayang Yu, and Tianqing Ling. “Laboratory Evaluation of Electromagnetic Density Gauges for Hot-Mix Asphalt Mixture Density Measurement.” Construction and Building Materials 158 (January 2018): 1055–1064. doi:10.1016/j.conbuildmat.2017.09.186.

[30] Leyland, R., and Amrita Maharaj. "Dielectric constant as a means of assessing the properties of road construction materials." South. African Transp. Conference (SATC) 2010 (2010).

[31] Fernandes, Francisco M., Andreia Fernandes, and Jorge Pais. “Assessment of the Density and Moisture Content of Asphalt Mixtures of Road Pavements.” Construction and Building Materials 154 (November 2017): 1216–1225. doi:10.1016/j.conbuildmat.2017.06.119.

[32] “Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures” Mix. ASTM Int. West Conshohocken, PA, USA (2005). doi:10.1520/d2726-09.

[33] Jaselskis, Edward J., Jonas Grigas, and Algirdas Brilingas. "Dielectric properties of asphalt pavement." Journal of materials in civil engineering 15, no. 5 (2003): 427-434. doi:10.1061/(ASCE)0899-1561(2003)15:5(427)