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# Field Assessment of Non-nuclear Methods Used for Hot Mix Asphalt Density Measurement

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**Abstract**

Destructive nature along with the associated higher cost of the traditional core method used for hot mix asphalt density measurement has convinced researchers switching to some non-destructive technique for this purpose which is cost efficient as well. Earlier, nuclear density gauges were introduced for this purpose which was non-destructive as well. Since such devices were associated with the use of gamma rays, therefore, leading to safety and health issues. Last decade observed a revolution in asphalt density measurement technique with the evolution of non-nuclear density gauges. This research work is carried out with the objective to determine the efficiency and accuracy of a newly developed non-nuclear density gauge i.e. PQI-380 for field conditions as it needs its thorough evaluation prior to future uses in many of the developing countries including Pakistan. Density data obtained using standard core method and non-nuclear density gauge for 195 location confirms the satisfactory performance of the instrument. Results obtained show that the coefficient of correlation is near to 0.9. Which refers to a strong correlation between the density data. Moreover, performance criteria e.g. root mean square error and mean absolute error between the density data set is also very low confirming the good measuring abilities of the device. Instrument performed well for repeatability analysis giving maximum coefficient of variance less than 5 percent.

*Keywords:* Core Method; Non-nuclear Density Gauge; PQI-380; Density Measurement.

## 1. Introduction

The density of hot mix asphalt (HMA) has vital importance in paving industries because of many prominent reasons. One reason, for example, includes challenges involved in maintaining, rehabilitating and managing the pavement structure due to the aging of the roads, and budget consideration for the developing countries in particular and the developed countries in general [1].

Moreover, the density of hot mix asphalt is the decisive factor in predicting the future pavement failure as a low density may increase the rate of deterioration and may have the chance of oxidation to occur moisture issues and may lead to cracking and ravelling [2-6]. On the other hand, density values that are higher enough thereby reducing the air voids content less than 3 percent may cause premature rutting [7]. Since the density of HMA plays a vital role in funds allocation for maintenance program along with its direct impact on the performance of the structure thus gaining a vital position among the researchers.

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Many of the developed countries have started using few non-destructive and latest techniques for density determination but still Pakistan along with many of the developing countries are using the traditional destructive core method for this purpose. Core method which is proceeded in accordance with American association of state highway and transportation officials (AASHTO) procedure AAHTO T-166 is associated with extracting the cores thereby associated with disturbing the pavement integrity [8]. Secondly, the core method of density determination is associated with time limitation as we need at least 24 hrs. to make the core sample air dried before measuring the density and artificial. Drying in an oven at the elevated temperature may distort the core sample thereby actual results may change [7].

Because of many problems associated with core method, researchers have always been in search of some method which do not require disturbing the pavement integrity. Nuclear density gauges were the first most developed way of HMA density measurement. A major problem associated with such kind of gauges involves health risk as they work on the principle of sending and receiving the scattered gamma rays [9]. Because of health risk associated, working with such gauges requires a very strict licensing. Moreover, these gauges were quite heavy in the past and operator need a scale to measure the density from a safe distance associated with the risk of health issues [10].

Despite being free from the problem of disturbing the road integrity, nuclear density gauges are said to be not as accurate as that of core method. The research concluded that five different models of nuclear density gauges showed different results varying from place to place and even from model to model at the same place [11]. Nuclear density gauges have been used for many years in many countries across the globe but still, there was a need for an equipment which is not destructive thereby bypassing core method along with being free from health issues as in case of nuclear density gauges [12].

Paving industry has seen revolutionary changes in the last ten years in the field of density measurement as industry witnessed non-nuclear density gauges. Measurement principle of Non-Nuclear Density Gauge (NNDG) is based upon sending and receiving electromagnetic waves thereby beating the issues related to health as in case of nuclear devices and disturbance of pavement integrity as in the case of core method [13].

This research work is done to assess the abilities of Electromagnetic, non-nuclear density gauge used for HMA density determination. This research work is primarily influenced by the research conducted to check the performance of non-nuclear density gauges. One research work has concluded that the density measured using one of the non-nuclear density gauges i.e. PQI-380 is statistically very different in comparison to standard core method [13]. Other research done to compare the results of three different non-nuclear devices to that of nuclear density gauges suggested that nuclear density gauges, on average, read the density value on the higher side. Research also concluded that some of the factors i.e. air voids, specific gravity, and pavement layer thickness affected the density reading determined through both the nuclear as well as non-nuclear density gauges [14]. Other research concluded that few factors including orientation of the gauge, moisture presence and marking paint have no significant impact on the gauge reading [15]. One of the researches done on non-nuclear density gauge compares the cost-effectiveness of both nuclear and non-nuclear methods and reaches to a conclusion that non-nuclear density gauges are more cost-efficient in comparison to nuclear ones [16]. One research conducted on non-nuclear density gauge stated that the number of the core can be reduced to a much lower level by the usage of such gauges [17]. In a study of Rogge and Jackson (1999), it is concluded that none of the density gauges has proved itself to be accurate enough to replace the standard method of density determination i.e. core method [18]. Non-nuclear, electromagnetic density gauges are said to be standard equipment for asphalt density measurement only when they produce results comparable to AASHTO T-166 [19]. One research work is carried out to check the efficiency of a non-nuclear method to assess the compactness uniformity of recycled asphalt pavement. The results have concluded that HMA density can only be predicted accurately if HMA is prepared as per the guidelines of manufacturer of the instrument. Moreover, instrument reduced the number of cores drilled out as the compactness of the pavement was assessed to a good level of accuracy using step frequency radar [20]. Leng et al. (2018) evaluate the non-nuclear density gauge under various laboratory-controlled conditions have concluded that the direction of placing the instrument has no effect on density readings. They also concluded that gauge efficiency is affected by different gradations, but it has no clear effect by the bitumen content [21]. Van den Bergh et al. (2017) carried out to monitor the compaction process concludes that immediate evaluation using density gauge is important to get accurate results. Moreover, this method is cost efficient and requires a smaller number of cores for density measurement. This method has also the associated disadvantages of training a person for density measurement along with the possible error in reading due to many local factors including temperature and moisture variations [10].

Abyad (2016) evaluate different non-nuclear devices for density determination concluded that non-nuclear density gauges are moisture and temperature sensitive. Their efficiency is greatly influenced by the gradation along with variation in the local climatic conditions [22]. Another research carried out to compare nuclear and non-nuclear density gauges concluded that although no-nuclear density gauges are more affected by the moisture present on the pavement surface but at the same time the results obtained by non-nuclear density gauges are more reliable in comparison to nuclear density gauges [9].

The present work is primarily influenced and inspired by the fact that the pavement industry is on a verge to maturity across Pakistan thereby enhancing the need for some accurate, rapid, non-destructive and cost-efficient method for HMA density measurement. Main objectives of the research include the following:

- Validation and evaluation of the non-nuclear density gauge in field conditions
- Performance verification of non-nuclear density gauges in comparison to standard core method.
- Establishing statistical correlation model between the density data obtained from both the core method and non-nuclear gauge to predict the core density from the non-nuclear density data.

Taxila institute of transportation engineering (TITE), to accomplish the above stated objectives arranged one of the latest available non-nuclear density gauges i.e. PQI-380 which uses the concept of impedance spectroscopy to measure the asphalt density. The results obtained from PQI-380 were compared to already existing standard core method to validate the efficiency of the gauge.

## 2. Research Methodology

This research work is designed to achieve the stated objectives: to validate the equipment under field conditions; and, to compare the density data obtained from the gauge and core method. In the first step of research, density data were obtained from NNDG from the selected sites which consist of freshly laid asphalt pavement as well as aged structure. From the same location, where density was determined using NNDG, we extracted the cores and measures the density in the laboratory. Finally, both the density data were compared, and a statistical correlation was developed so that one can predict the core density even without extracting the cores in real practice. In the coming lines, a brief introduction to the working principle of non-nuclear density gauge is explained. Then the site selection for density determination, general characteristics of the material used in the pavement structure is described.

### 2.1. Non-Nuclear Density Gauges

PQI-380 determines the density of asphalt pavement by emitting the electromagnetic rays. These rays when hit the pavement surface i.e. HMA which is nonconductor material losses its strength. The amount by which this electric field reduces its strength is referred to as dielectric constant of the material. Density estimation by the gauge is carried out by the reduction in electromagnetic rays strength which is displayed on the screen [23, 24].

Non-nuclear density gauges on average have similar characteristics. Major characteristics of the non-nuclear density gauge used in this research work are enlisted in Table 1.

**Table 1. General characteristics of PQI-380**

| **General specification of NNDG** | |
|---|---|
| Area of sensor | 11 inches (27.9mm) of sensor ensures the density measurement |
| Depth range | NNDG has the density measurement for the range of 25-100 mm |
| Temperature sensitivity | Accurate density determination can be ensured by taking measurement in the range of 0-350˚F |
| Accuracy | PQI-380 has the accuracy of ±1.5 % |
| Screen display | PQI-380 has VGA display of 480 X 640 |

Operation principle of electromagnetic density gauges i.e. Pavement quality indicator (PQI) is shown in Figure 1 where a transmitter is shown from which the rays are introduced to the pavement surface and the other one being the receiver that collects the scattered rays. Pavement quality indicator works on a constant voltage, low frequency, electrical impedance approach. The density of HMA measured using NNDG is highly affected by the types of material used in asphalt mix as HMA comprise of many components and for each component, dielectric constant varies considerably e.g. air, 1; water, 80; aggregate, 4-20) [25].

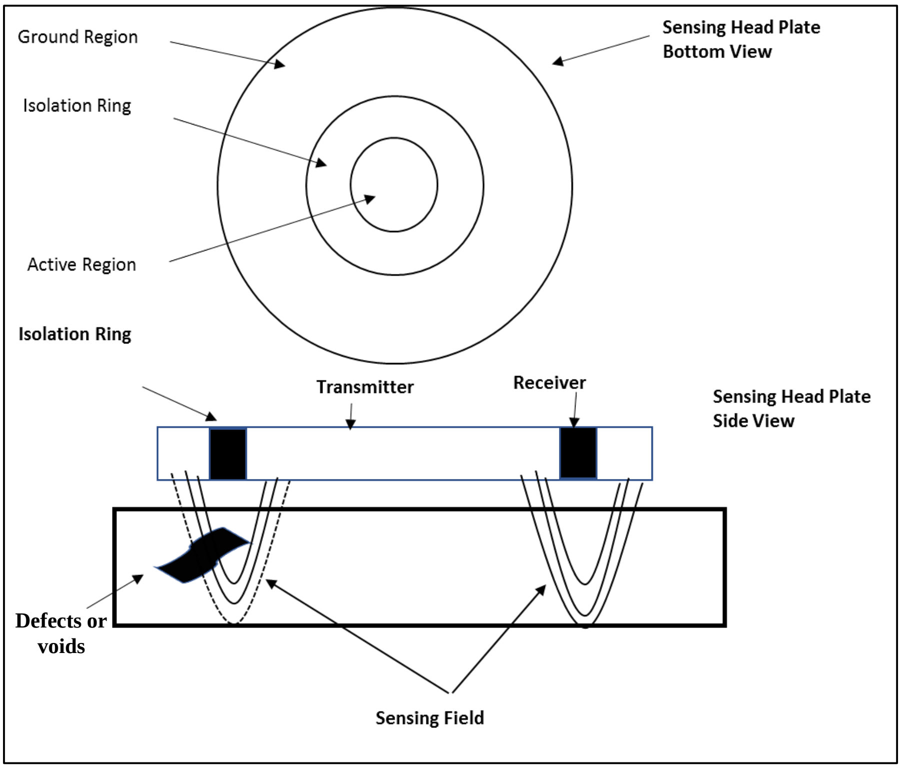


**Figure 1. Schematic diagram for electromagnetic density gauge**

Non-nuclear density gauge i.e. PQI-380 used for this research work is shown in Figure 2.

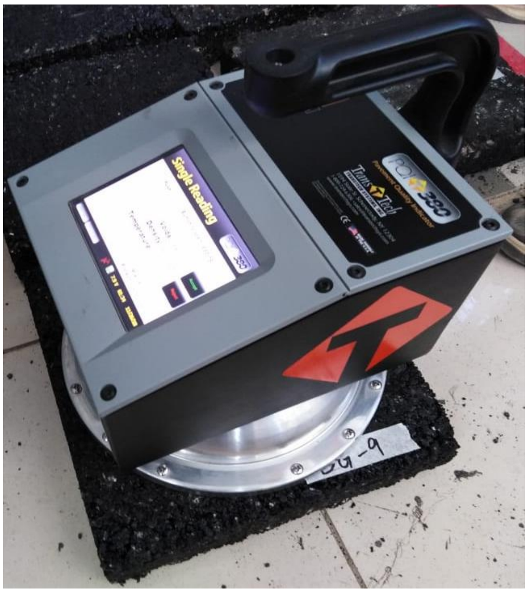

**Figure 2. PQI-380 used for the research work**

## 2.2. Site Selection for Field Studies

This section elaborates the sites selected for the field testing. First sites selected for performance verification is explained and then basic and fundamentals of the selected sites i.e. aggregate gradation along with properties of the binder materials are also explained. Field studies were done to compare the densities obtained using NNDG and Core methods. It included a total of 195 cores extracted from two different sites. One of the sites was near Sahiyan wala interchange on Faisalabad Multan motorway M-4. Total of 150 cores were extracted from this location during high-temperature conditions. Aggregate gradation used for this site was dense gradation. Google map image is inserted for the first site as shown in Figure 3 While another site was a service road in Rawalpindi Gulberg green. Total of forty-five cores were extracted from this site during low-temperature conditions. This road was also constructed using dense gradation and cores were extracted for wearing course. Google map image for this site is inserted as shown in Figure 4

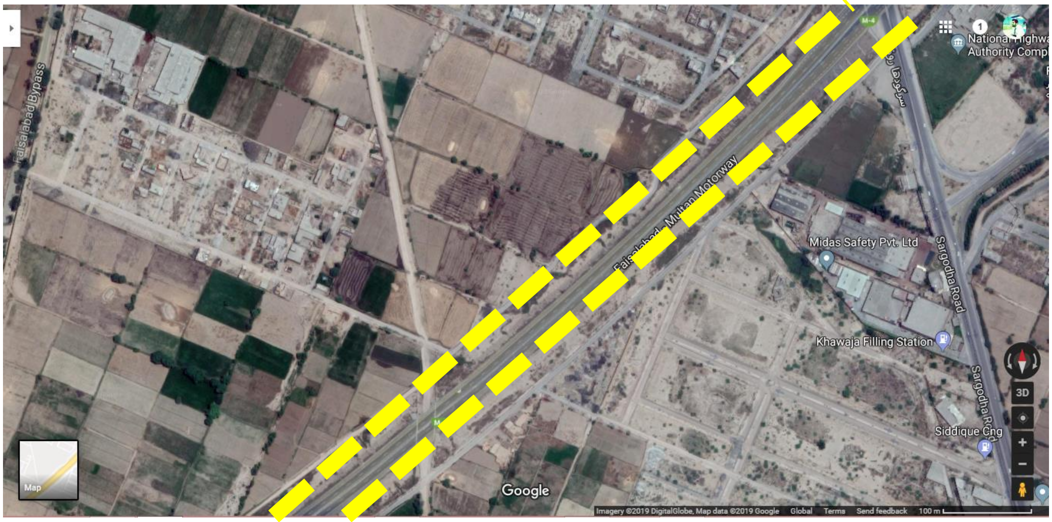


**Figure 3. Google map images for selected sites: Faisalabad-Multan motorway (Sahiyyan wala interchange)**


**Figure 4. Google map images for selected sites: Service road west Gulberg green**

As it is already discussed that for both the selected sites, dense graded aggregates are used as per NHA-B. Gradation curves for NHA-B is shown in Figure 5.

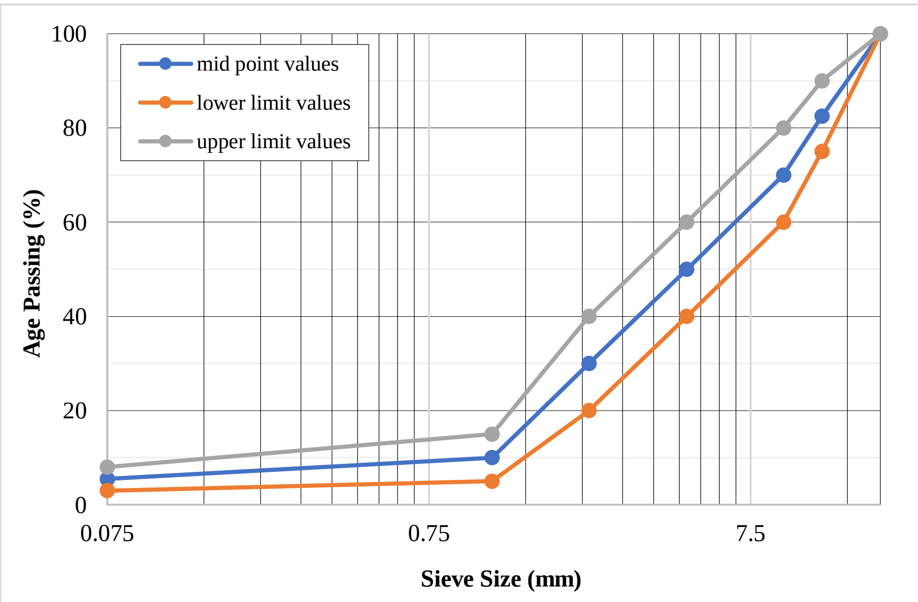


**Figure 5. Gradation curve for NHA-B; Dense gradation**

A flow chart is shown in Figure 6 that describes the methodology of this research work. The research includes the testing that covers checking the effect of calibration for field density determination. Purpose of doing calibration is to increase the accuracy of the results obtained from field conditions. Effect of calibration is checked by preparing the slabs in the laboratory so that possible effect can be accomplished.

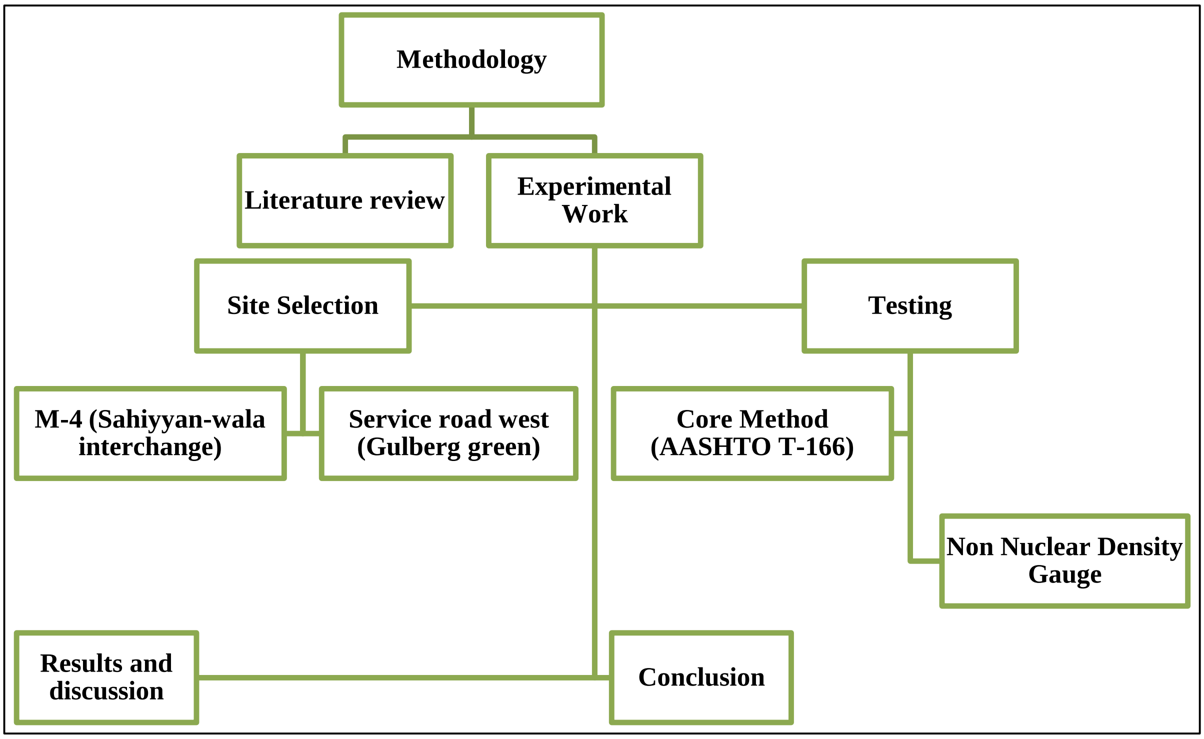


**Figure 6. Flow chart describing the methodology of research work**

## 3. Results and Discussion

Major outcomes from the tests carried out in order to meet the stated objectives are described in this section. First, the density data from both the technique is compared and checked against whether the results are statistically similar or not. Moreover, for both the sites a statistical correlation model is developed so that one can predict the core densities without extracting the cores for future work. In this way, this study clearly gives a relation based on correlation developed for a huge number of extracted cores.

### 3.1. Field Results

For field assessment of the non- nuclear density gauge total of 195 locations were selected and the density data using the gauge is determined. Secondly at the same location cores were extracted and the density is also measured in the laboratory as per AASHTO T-166. Density determination using NNDG and core method is shown in Figure 7 (a) and (b) respectively.

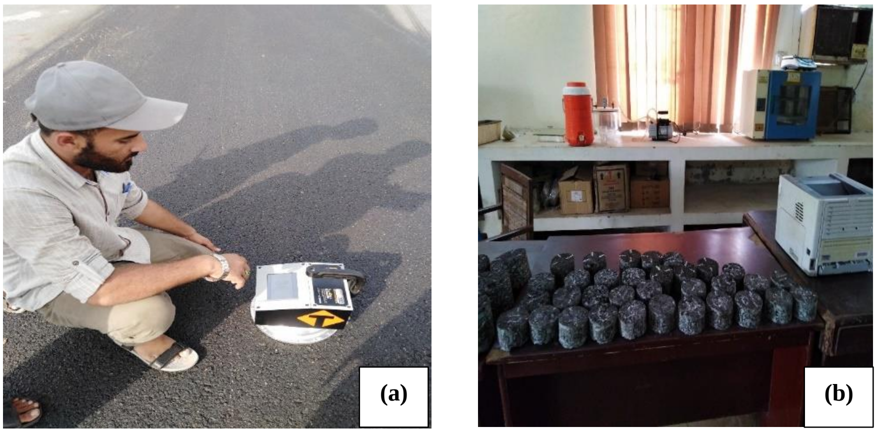


**Figure 7. density determination using two methods: NNDG (a) and drilled cores for laboratory density measurement**

A linear regression model is developed from the field data in order to check whether the results from both the methods are comparable or not. Moreover, on average, how the NNDG reading is varying for both the hot and low-temperature range is explained and elaborated and lastly, a correlation equation is developed for both the temperature conditions so that one can predict the core density even without extracting the cores. The basic purpose behind the development of the equation is to minimize the core extraction.

For site 1 i.e. Sahiyan wala interchange on M-4, It is shown in Figure 8 where a scattered chart is plotted between the two densities data. The graph has density measured using NNDG on Y-axis while X-axis carries the density data obtained from the core method. Core density being the independent variable is plotted on X-axis while NNDG being a dependent variable is plotted on Y-axis. This plot confirms that under high-temperature conditions NNDG performance is satisfactory as the value of the correlation coefficient is 0.752 which means that using this model 75.2 percent of core density data can be predicted accurately and vice versa. For the best correlation, this coefficient is said to have the value near or equal to 90 percent. At the same time, the value of 0.752 is acceptable as the data is for 150 points. Hence, it can be concluded that 75.2 percent of accurate prediction of density data is enough to say that NNDG i.e. PQI-380 has performed well for field conditions of high-temperature range.

Similarly, a correlation model is developed for the second site i.e. service road at Gulberg green as shown in Figure 9. For this site, a correlation coefficient is on a higher side which is 0.82. The value of correlation coefficient confirms the satisfactory performance of NNDG under low temperature as well. Therefore, from these results, it can be concluded that NNDG performed satisfactorily under field conditions of varying temperature.

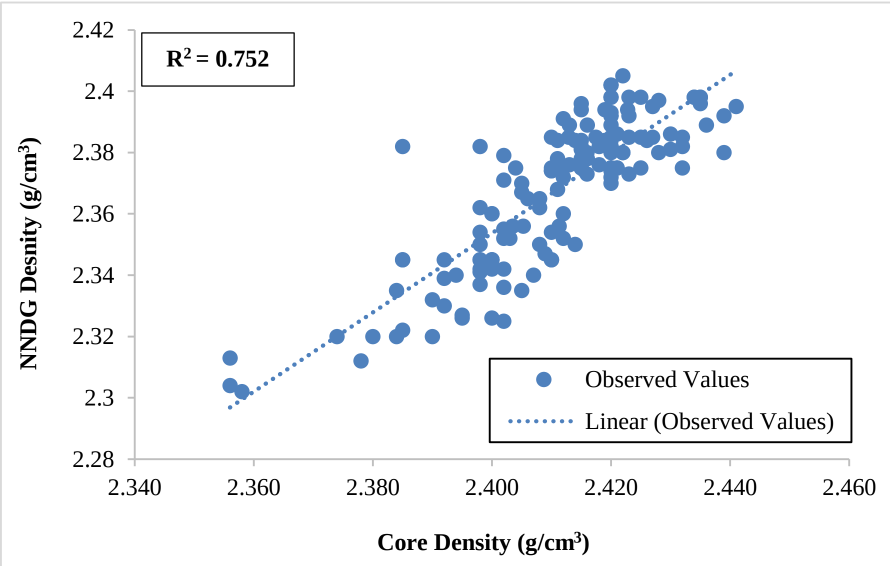


**Figure 8. A linear model developed for Site 1; Sahiyan wala interchange (Faisalabad Multan motorway)**

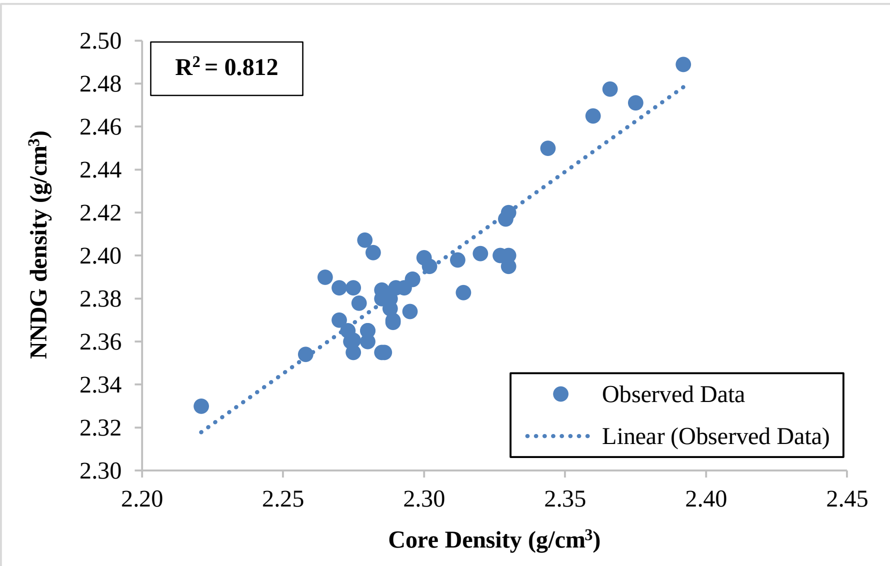


**Figure 9. A Linear Model developed for site 2; Service road west Gulberg green**

The results obtained from developing a correlation says that on average for both the sites, PQI-380 has shown results that are quite correlate able to already existing standard core method. therefore, such gauges have a bright future to be used in the field of asphalt density measurement as a sole replacement to core method. The field results were analysed in a different perspective to check whether the mean of the two methods are statistically different from each other. For this purpose, bar charts are plotted for both the sites which contain average density on Y-axis while two bars are shown representing both the methods. It is shown in Figure 10 that NNDG value is on lower side in comparison to that of core method. The percentage difference between the density data is only 1.79 percent. While on the other hand for site 2 i.e. Service road near Gulberg green it can be seen form the Figure 11 that NNDG reads density value higher in comparison to density data obtained from core method. The percentage difference between the density data is 4.01 percentage.

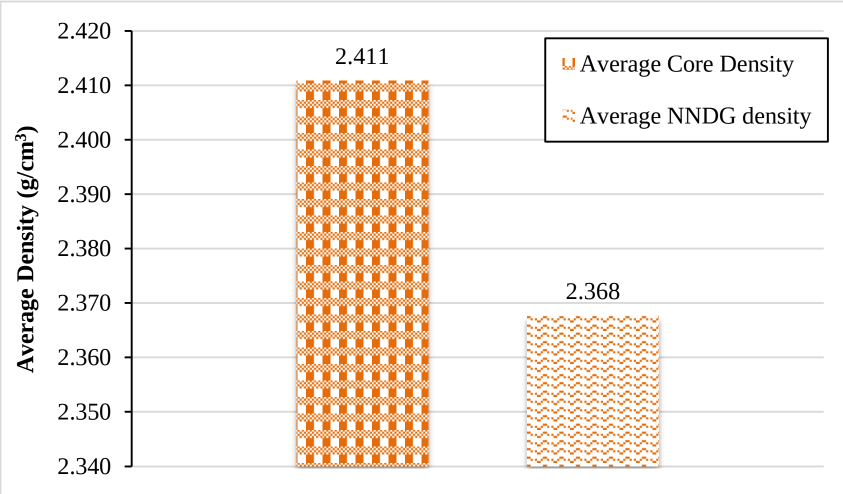


**Figure 10. Average density data for site 1; Sahiyan wala interchange (Faisalabad Multan motorway)**

It has been concluded by the researchers that the temperature may affect the electrical conductivity of asphalt concrete [25]. Average NNDG density to be on the lower side for site 1 where the temperature was on a higher side and to a higher side in the case of the second site, where the temperature was on the lower side, can be explained by the above-mentioned temperature effect on the electrical conductivity of asphalt. Moreover, researchers have also stated that different material may exhibit different rate of change in dielectric constant for same temperature variation [26].

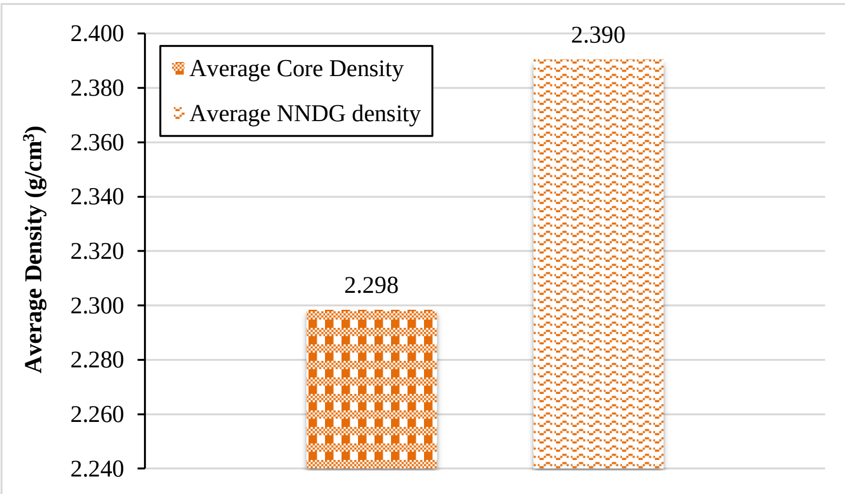


**Figure 11. Average density data for site 2; Service road (gulberg green)**

Accuracy of non-nuclear density gauge can be improved if the temperature sensitivity of the instrument is decreased. Although it has shown the results that are comparable with the results obtained using the core method still there is a need to determine the effect of temperature on the gauge reading. The efficiency of the instrument can be enhanced by making the instrument less temperature sensitive.

It can be seen from the Table 2 maximum mean absolute error (MAE) for both the sites is 0.015 while other performance evaluation criteria also states the satisfactory performance of the instrument.

**Table 2. Performance criteria for both the sites**

| Performance criteria | Site 1 Model data set | Site 2 Model dataset |
|---|---|---|
| $r^2$ | 0.752 | 0.82 |
| RMSE | 0.009 | 0.012 |
| MAE | 0.008 | 0.015 |

Root mean square error in the data set is even below 5 percent that means the PQI-380 has a huge potential to be used for asphalt density measurement.

### 3.2. Predicting the Core Densities

One of the objectives of this research includes minimizing the number of cores extraction for future work so that pavement integrity is disturbed to a minimal level. For this purpose, this research suggested two equation which holds good for two temperature ranges i.e. lower and higher one.

Equation 1 holds valid for lower temperature conditions that has temperature range of 0 to 15˚C while Equation 2 is valid to predict core density from NNDG data in high temperature conditions ranging from 15 to 35˚C.

$$DCore = 0.9396 \times DNNDG + 0.2308 \quad (1)$$

$$DCORE = 1.2918 \times DNNDG - 0.4767 \quad (2)$$

Where $D_{Core}$ = density of the asphalt pavement measured using core method (g/cm$^3$) and $D_{NNDG}$ = Density of the asphalt pavement measured using NNDG i.e. PQI-380 (g/cm$^3$)

This research work has a prime objective of decreasing the number of core extraction as this activity has long-lasting effects on the pavement structure and it disturbs the pavement integrity. These two equations were developed so that core density for any of the pavement can be predicted just by knowing the density of that point using NNDG under the varying condition of temperatures.

### 3.3. Repeatability Analysis

Repeatability of the EM density gauge was verified by measuring the density of each location for at least ten times. Each time instrument was lifted 2 inches high and then placed again at the same point. For better graphical representation five locations were set for both the sites and density was measured ten timed. Repeatability test for site 1 and site 2 is shown in Figure 12 and 13 respectively.

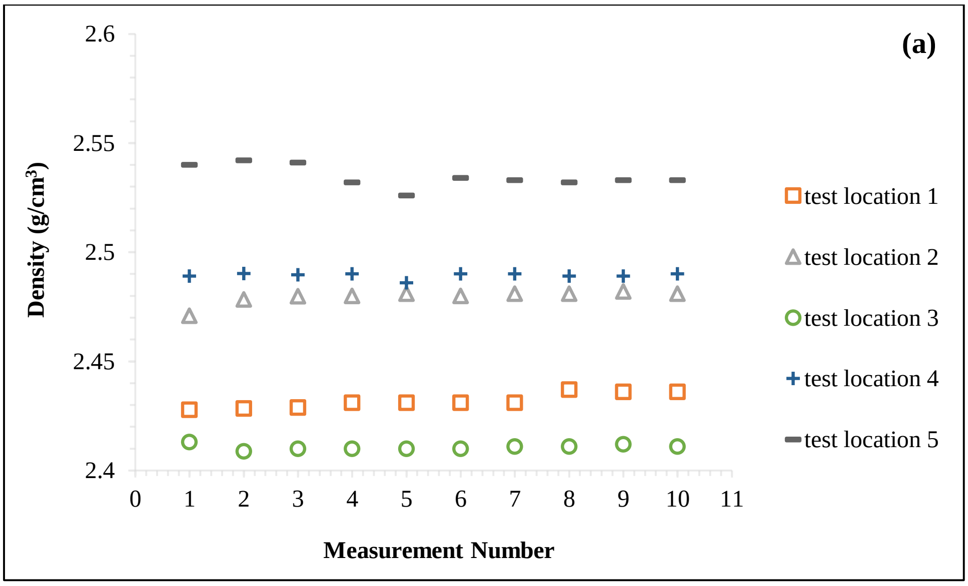


**Figure 12. Repeatability analysis for site 1; Sahiyan wala interchange (Faisalabad Multan motorway)**

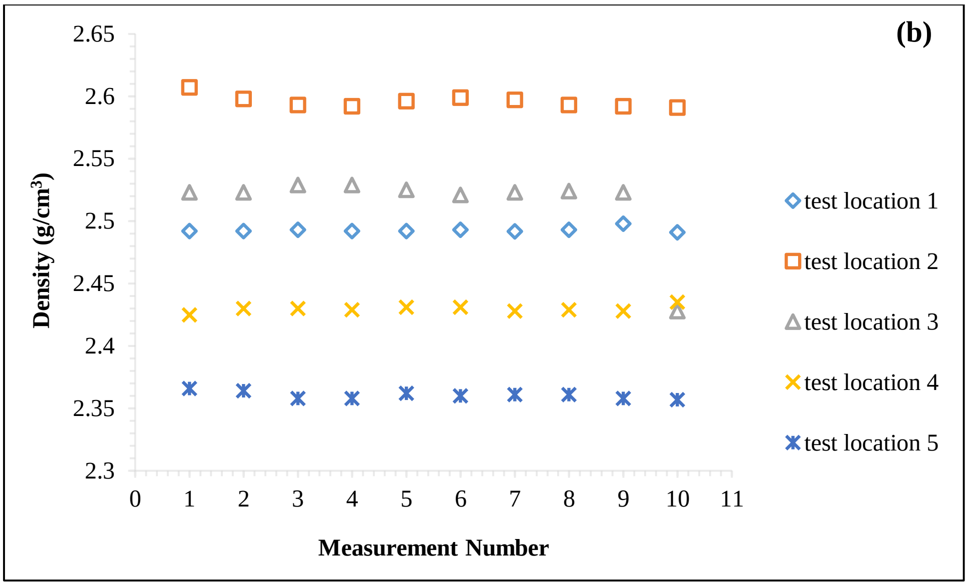


**Figure 13. Repeatability for site 2; Service road west Gulberg green**

Results indicated that for site 1 at Sahiyan wala interchange prepared as per NHA-B having high-temperature conditions, the coefficient of variance comes out to be 0.12 percent as shown in Figure 14. This value is much lesser indicating the instrument has results comparable enough as it will show almost similar results taken at a different time for the same location. Similarly, for the second site at service road west near Gulberg green, the coefficient of variance was 0.21 percent as shown in Figure 14. This value showed that for the repeatability, instrument performed well enough. In comparison to the first site (high-temperature conditions) results show that performed of non-nuclear density gauge is way better than for low-temperature condition as for repeatability coefficient of variance is less.

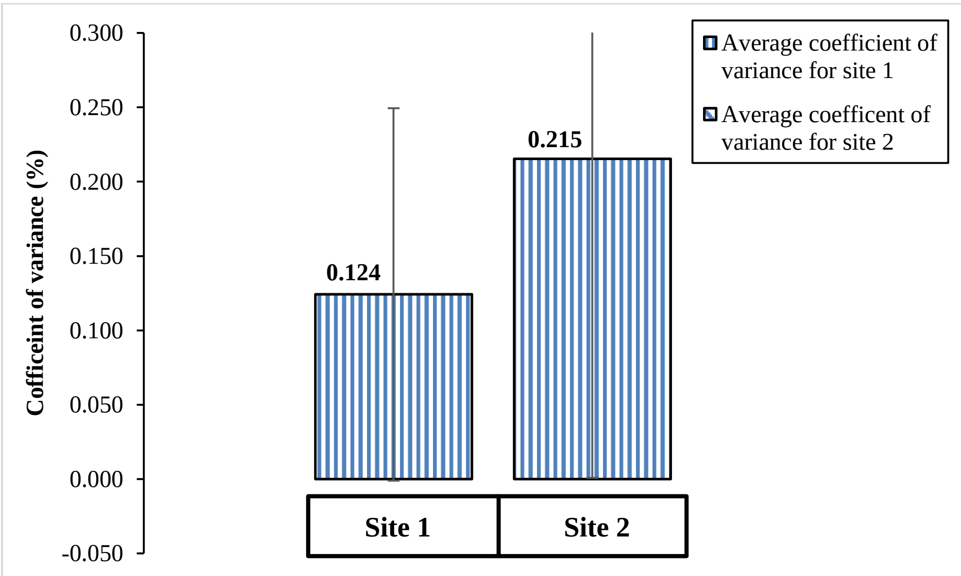


**Figure 14. Average coefficient of variance for both the site**

## 4. Conclusions

This research work covered performance verification of non-nuclear density gauge for field condition. Major results obtained from the research are elaborated below:

- Field study conducted to evaluate the performance of non-nuclear density gauge concludes that the instrument performed well under field conditions of varying temperature. Coefficient of correlation from both the sites are near to 0.9 on average making it more comfortable to rely on the performance of NNDG.
- Maximum percentage difference between the density data obtained from both the sites confirms that this difference is even less than 5 percent.

- This research work highly recommends use of NNDG i.e. PQI-380 for asphalt density measurement for future only if the results are comparable to that of already established standard core method results.
- Repeatability analysis have shown that NNDG produces similar results measured for same location at different times. This thing encourages the author to conclude that PQI-380 produces more consistent results.

This study has recommendations to go for a detailed evaluation of such gauges involving their cost effectiveness. Such gauges should be evaluated based on their performance under varying climatic conditions e.g. temperature, moisture and different raw debris presence on the pavement.

## 5. Acknowledgement

All praise to Almighty Allah, the creator of everything. Authors show huge regards for national highway authority (NHA) of Pakistan for allowing the access to the core extraction. Authors also acknowledge the efforts of capital development authority (CDA) for providing the density data for cores from service road west near Gulberg green, Islamabad, Pakistan.

## 6. Conflicts of Interest

The authors declare no conflict of interest.

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