Nuclear gauge application in road industry

Mohd Azmi Ismail

1Industrial Technology Division, Malaysian Nuclear Agency, Bangi, 43000 Kajang, Selangor, Malaysia
Corresponding author: azmi@nm.gov.my

Abstract. Soil compaction is essential in road construction. The evaluation of the degree of compaction relies on the knowledge of density and moisture of the compacted layers is very important to the performance of the pavement structure. Among the various tests used for making these determinations, the sand replacement density test and the moisture content determination by oven drying are perhaps the most widely used. However, these methods are not only time consuming and need wearisome procedures to obtain the results but also destructive and the number of measurements that can be taken at any time is limited. The test can only be fed back to the construction site the next day. To solve these problems, a nuclear technique has been introduced as a quicker and easier way of measuring the density and moisture of construction materials. Nuclear moisture density gauges have been used for many years in pavement construction as a method of non-destructive density testing. The technique which can determine both wet density and moisture content offers an in situ method for construction control at the work site. The simplicity, the speed, and non-destructive nature offer a great advantage for quality control. This paper provides an overview of nuclear gauge application in road construction and presents a case study of monitoring compaction status of in Sedenak - Skudai, Johor rehabilitation projects.

1. Introduction

Effective control of compaction of soil and stone layers is an important factor in the construction of roads and other types of foundations for civil engineering structures [1]. Compaction is a process of increasing soil density or unit weight, accompanied by a decrease in air volume, with the intention to improve strength and stiffness of foundation materials. The failure to displace air from between soil particles may lead to unwanted soil movement and water penetration into the earth beneath the foundation.

To achieve a uniformly compacted base and sub-grade, one needs to be able to measure it. In the traditional content, the roller operator feels the level of compaction through their seat and makes adjustments according to this. Every operator has a different learned experience for what is acceptable or not [2]. The degree of compaction is measured by dry unit weight and depends on the water content. The maximum dry unit weight occurs at an optimum water content. There are several techniques that can measure the dry density and moisture content of the soil. Conventional methods such as the sand replacement density test the moisture content determination by oven drying are perhaps the most popular [3]. However, these methods are not only time consuming and need a wearisome procedure to
obtain results but they are also destructive and the number of measurement that can be taken at any one time is limited. The results of the test can only be fed back to the construction site the next day [4].

To solve this problem, a quicker and easier way of measuring soil density and other properties of construction materials is required. Various methods have been studied and among them was nuclear technique. Nuclear moisture density gauges are testing devices that use low-level radiation to measure the wet density, dry density, and moisture content of the soil and granular construction materials. This technique which can determine both wet density and moisture contents offers an in-situ method for compaction control at the work site. Its simplicity, speed, and non-destructive nature offer a great advantage for quality control compared to other conventional methods.

2. Radiation interaction with matter

2.1. Interaction of gamma rays

When a gamma ray passes through medium, successive interactions occur which the constituent atoms and energy of the gamma ray decrease gradually. Interaction takes place between the gamma ray and the atoms and the following three kinds of interactions are known:

2.1.1. Photoelectric absorption. This is the ionization of gamma ray in which the difference between the initial gamma ray energy and the binding energy of the orbital electron will be taken away by the released electron as its kinetic energy (figure 1). The differential cross-section ($\sigma_{\gamma p}$: a probability of interaction) depends on the initial gamma ray energy ($E$) and atomic number ($Z$), and can be written approximately by the following equation:

$$\sigma_{\gamma p} \propto \frac{N_0}{E^n}$$

where, $n = 3$ (for low energy gamma ray) and $n = 5$ (for high energy gamma ray)

Contribution of photoelectric absorption to the attenuation of gamma ray will become important when the low energy gamma rays pass through a medium of large atomic number.

![Figure 1. Schematic presentation of gamma ray interaction with matter - photoelectric absorption.](image)

2.1.2. Compton scattering. It is an elastic scattering between the gamma ray and the orbital electrons in which total kinetic energy, as well as total momentum, are conserved throughout the scattering (figure 1). The energy of gamma ray after scattering can be written as a function of its initial energy ($E_0$) and scattering angle ($\theta$) in the centre of the mass system.
\[ E = \frac{E_0}{1 + \left( \frac{E}{m_0 c^2} \right) (1 - \cos \theta)} \]  

where, \( E_0 \) = initial energy gamma ray, \( m_0 \) = rest mass of electron, \( c \) = velocity of light

Cross section of the Compton scattering \( \sigma_c \) depends on the energy of gamma ray \( E \) and atomic number of the medium \( Z \) as follows,

\[ \sigma_c \propto \frac{1}{E} \]  

In Compton scattering, part of the initial energy of gamma ray will be lost during collision with the electrons (figure 2), but not all as in the case of photoelectric absorption. Therefore, after several successions of Compton scattering, the probability of the photoelectric absorption becomes greater until finally gamma ray disappears.

Figure 2. Schematic presentation of gamma ray interaction with matter - Compton scattering.

2.1.3. Pair production. In this interaction, a gamma ray with an energy greater than twice of electron mass energy (nearly 1.02MeV) disappears near the nucleus of the material and a pair of electron and positron is created (figure 3). The dependency of the cross section of the interaction on \( E \) and \( Z \) can be written as follows:

\[ \sigma_{\text{pp}} \propto \frac{1}{E} \left( E - 2m_0 c^2 \right) \]  

where, \( m_0 \) = rest mass of electron \( c \) = velocity of light

The energies of the gamma rays emitted from \(^{60}\)Co are 1.17 and 1.33 MeV, the difference of which from the threshold of pair production is very small so that we can actually neglect the effect.

2.2. Interaction of neutron

A neutron is an electrically neutral particulate radiation. Being uncharged, the neutron can go through any material with little interaction with surrounding atoms. The high transparency of neutron makes it very different in character as compared with an electron or any other electrically charged particles. Neutron interaction with the material is only by nuclear force. In another word, only the nuclei of atoms have the capability to stop or slow down the neutrons.
Neutrons emitted from a neutron source are part of the product of nuclear interaction taking place in the source. The possible energy of the produced neutron varies one type of neutron source to another, ranging from near 0 to 11 MeV and the mean energy is in the order of several MeV. The significant of the neutron energy in the interaction of the neutron with matter makes it necessary to classify neutron according to their energies. The terms thermal, epithermal and fast each represents a broad, rather indefinite range of neutron energies. Thermal neutrons are those which have reached thermal equilibrium with their surroundings (less than 0.5 eV). Epithermal neutrons are within the group of thermal and fast neutrons. The lower boundary of fast neutron group is quite arbitrary, perhaps about 100 KeV.

The nature of interactions between neutron and atomic nuclei will depend both on the energy and nature of the nucleus. Practically, these are classified as absorption or capture and scattering reactions. Only those interactions with an appreciable probability of occurrence within the energy range from 11 MeV down to thermal energies are of interest in moisture measurement.

3. Nuclear moisture density gauge

3.1. Density measurement

Density measurement is based on the fact that the intensity of the transmitted gamma ray depends strongly on the density of the measured material. The flux of directly transmitted gamma ray can be given by the following well known empirical equation [5].

$$\phi = S_0 e^{-\mu x}$$

where, $\phi$ = flux, $S_0$ = initial source intensity, $x$ = distance between the source and the centre of the detector, $\rho$ = density of the material, and $\mu$ = mass absorption coefficient.

Under the normal circumstances of measurement, a considerable amount of secondary gamma ray which is scattered in the medium will also be included in the detected flux. The contribution is signified by a term known as Build-up Factor, $B$. Therefore, in terms of count rate, (6) can be written as the following:

$$N = n_0 e^{-\mu x}$$

where N is the number of atoms.
In general, \( B \) is not only a complex function of the decay length \((\mu L)\) but also depends on the type and dimensions of the detector. However, in the design of density gauge, the following simple equation is adopted, applicable for a specific and appropriate range of material density.

### 3.2. Moisture measurement

In the measurement of water content (moisture) of soft ground, such as embankment, direct transmission gauge is more widely used. Transmitted fast neutrons from the source are slowed-down during interaction with the nuclei of the constituent atoms. As mentioned earlier, fast neutrons can lose maximum energy when they collide with hydrogen nucleus. The number of fast neutrons will decrease as more hydrogen is present in the soil. Therefore, fast neutron counting rates are roughly expressed as an exponential function of moisture content (water density),

\[
R_m = e^{-B m_m} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)
\]

where,

- \( R_m \) = neutron count rate, \( A, B \) = calibration coefficient, and \( m_m \) = moisture content

Hydrogen presents in the soil in many forms. It may exist as absorbed water (water content), crystalline water and in organic materials. In civil engineering works, we are only interested in the water content which is evaporated at 110°C in the oven. Other types of waters (so called ignition loss) remain in the soil after the drying process. Unfortunately, neutrons interact with all types of hydrogen in the soil and cannot distinguish between them. Therefore, when using the nuclear gauge, correction of ignition loss has to be made. This is done by introducing a moisture corrective coefficient, \( \varepsilon \). From (8),

\[
R_m = e^{-B \varepsilon m_m} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)
\]

where,

- \( \varepsilon m_m \) = equivalent neutron content (\( \varepsilon m_m = m_m + \varepsilon_d \)), \( \varepsilon \) = moisture content corrective coefficient, \( \varepsilon_d \) = dry density, and \( m_m \) = moisture content

### 3.3. Field measurement

The instrument introduced in this paper is a compact surface gauge of direct transmission type which employs a radiation source with a strength of 8 mCi of \(^{137}\text{Cs}\) and 40mCi of \(^{241}\text{Am}:\text{Be}\). Both the density and moisture gauges are incorporated into the instrument hence it is often called a combined gauge. Modern gauges offer optional features such as GPS location, remote start keypad near the handle, backlit keypad and external beeper [6].

### 3.4. Calibration procedure

#### 3.4.1. Calibration equation for different types of soil

To compute density and moisture content from a measured amount of transmitted radiation, it is necessary to derive a conversion formula (calibration curve) beforehand. In the early design, only a single calibration curve of a particular type of soil can be stored in the gauge at one time. Since various kinds of soil are normally dealt with during construction of road earthwork, a different calibration curve has to be drawn every time the soil type changes. To overcome this problem, a single calibration curve which is applicable to various types of soils was studied.

A calibration test on 17 types of soil sample ranges from coarse- to fine-grained soils under 144 different conditions of densities and moisture contents were conducted. The results of the test for
density and moisture is plotted in figures 4 and 5, respectively, before and after corrections for interference by neutron-capture gamma ray to density measurement and effect of dry density and ignition loss to moisture measurement are made.

Although there are some scattered points in the calibrated data indicated in these figures, we can safely conclude that a single calibration curve could be applied to all kinds of soil tested. Scattered data could be due to the heterogeneity of the soil samples.

3.4.2. Calibration for individual gauge. In actual measurement, a calibration curve must be programmed in the gauge beforehand. There are, however, some differences in the mechanical characteristics of each gauge and each gauge must have its own calibration curve.

Calibration for each gauge is carried out using a material of constant density and moisture content. The response characteristics of the gauge are recorded as standard values. Once a calibration curve is obtained, it is usable for any site unless the radiation source is replaced.

4. A Case Study
PLUS Malaysia Berhad has conducted a rehabilitation project on North - South Expressway at KM9.57, south bound of Kempas - Skudai Expressway. The road surface was deteriorated and needs to be replaced. PLUS has decided to reconstruct the road base using Cement Bound Material (CBM),
The status of compaction of the CBM need to be evaluated within hours after placement because it will harden. Conventional techniques require a longer time to evaluate the dry density and moisture content of the CBM material, for instance, the determination of water content using oven will require at least 12 hours. The nuclear gauge was used for assessment of compaction of the CBM was used with throughout the project and took only one-minute measuring time per each spot.

Figure 6. The problem of the deteriorating road surface.  
Figure 7. The status of compaction was finally checked by nuclear gauge.

5. Conclusion
In conclusion, compaction is one of the most important processes in roadway construction. A uniform sub-base and sub-grade is a key ingredient in maximizing pavement performance and the stiffness of the sub-grade is a major contributor to this uniformity, whether it is in pavements, road embankments or bridge abutments. The determination of the status of compaction by nuclear technique has the following advantages:

i. The method is non-destructive and repeatable.
ii. Results for moisture and density at a single point can be obtained within minutes.
iii. The method is accurate and easy to perform, minimizing human error.
iv. The collection of as many sampling data as required can be done without any difficulty.
v. The status of compaction can be fed to the construction work instantly with confidence.

6. References
[1] Huet J 1965 Field determination of moisture and density in soils by nuclear methods, in A. Wexler ed., Proceedings International Symposium on Humidity and Moisture, Van Reinfold and Co., NY 185-193
[2] IAEA Technical Report Series 1970 Neutron moisture gauges
[3] Toyama M 1990 Compaction control by nuclear method in highway embankment. Paper presented at the NEMS on the use of Nucleonic Control System and Nuclear Instruments in Civil Engineering. Kuala Lumpur, Malaysia
[4] Power R 2013 The changing face of Compaction and Compaction Control for road building – a Global Review
[5] Nobuyama M 1988 Density measurement and its application to compaction control of the embankment. Paper presented at the NEMS on the use of Nucleonic Control System and Nuclear Instruments in Civil Engineering. Kuala Lumpur, Malaysia
[6] Troxler Electronic Laboratories, 2017. Surface nuclear gauges
[7] Mohd Azmi Ismail and Kanesan Sinnakarupan. 1993. The in-situ density measurement for CBM at km 9.57 south bound of the Kempas - Skudai Expressway. A report submitted to Projek Penyelenggaraan Lebuhraya Berhad (PROPEL)

Acknowledgement
The author is grateful to Malaysian Nuclear Agency for support and for sponsoring the training in this field. Thanks also are due to Japan Highway Public Corporation, Soil and Rock Engineering Co. Ltd, Kajima Corporation for supervision and discussion during the author's stay in Japan.