Determination of Correlation Between Nuclear Moisture Density Tests and Standard Tests on Certain Gravel Bases in South Arkansas

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16. Abstract

The nuclear method presented inconsistent results when applied to density and moisture of a gravel base material in the Southwest, AR, Nashville area. Nuclear wet densities were lower (4-18 pcf) than the sand cone wet densities. Nuclear moistures appeared to be higher than the oven dry moisture. The gravel base being tested presented high field dry densities (sand cone method) in the range of 133 to 150 pcf. The nuclear gage in use was a Troxler 3411-B model.

In order to investigate the correlation between nuclear and actual density and moisture, and to develop new correlation between curves, six gravel base samples (1.1 cu. ft.) were compacted in the laboratory, and nuclear tests performed on them. The actual density (weight/volume) and the oven dry moisture was compared to the nuclear density and moisture.

A correlation study between laboratory nuclear and actual results showed (1) that the correlation nuclear-actual wet density is linear and the difference between them increases as wet density increases; (2) that nuclear moisture can be lower as well as higher than the oven dry moisture and the correlation between them is linear also; (3) that nuclear-actual dry density correlate very poorly.

New density and moisture calibration curves for the Nashville, AR, gravel base material are presented.

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Nuclear moisture/density, correlation, gravel base course, statistical analysis

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DETERMINATION OF THE CORRELATION BETWEEN NUCLEAR MOISTURE/DENSITY TESTS AND STANDARD TESTS ON CERTAIN GRAVEL BASES IN SOUTH ARKANSAS

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IMPLEMENTATION

There is a lack of correlation between nuclear dry density and laboratory dry density. However, linear relationships do exist for wet density and moisture content. These can be developed for a particualr soil by either field or laboratory determinations. Using the corrected vlaues of wet density at a particular moisture content, the dry density may be calcualted. There is no single factor that can be used to correct dry density due to the plus and minus deviations of nuclear moisture from actual moisture.

GAINS, FINDINGS. AND CONCLUSIONS

The following items are the primary gains and conclusions of this study.

1. On certain south Arkansas soils, the errors in nuclear moisture/density measurements are significant. The wet density error increases as density increases. The moisture content error is negative at low values and positive at high values.
2. A significant linear correlation exists for both wet density and moisture content. It does not exist for dry density. Dry density must be calculated using the corrected wet density and corrected moisture content.
3. Field and laboratory results indicate a probable source of error is the soil material being tested. All other errors have been investigated. Additional research will be necessary to confirm the source of error. For purposes of this project, such research would be basic rather than applied.

SUMMARY OF IMPLEMENTATION

Practical Application: Use or Procedures to calibrate nuclear device for particular soil type will allow the nuclear m/d device to be properly used for field control.

Recommended Procedure: A straight-line plot or table can be developed by using nuclear generated values versus either sand cone or laboratory derived values. Dry density can be determined from corrected moisture content and corrected dry density. Do not attempt to use a factor to modify dry density since no correlation was found to exist.

Benefits: Savings in time and money are possible by using nuclear device. Valid data can be determined by this method rather than the practice of modifying nuclear dry density data.

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AND
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RECOMMENDED IMPLEMENTATION OF TRC 70

As stated in TRC 70 "Determination of the Correlation Between Nuclear Moisture-Density Tests and Standard Tests on Certain Gravel Bases in South Arkansas", the moisture-density gauges provide inconsistent results when determining the moisture content and the dry density of gravel base courses. The following recommendations are steps that can be taken to minimize the stated problem.

1. Instruct the District Materials Supervisors in proper gauge operations so that they will be able to provide consistent instruction to regular gauge operators.
2. Prepare an easy to read and understand instruction manual on gauge operation.
3. Maintain daily logs of standard counts on each gauge in order to detect gauge deterioration.
4. Reestablish the calibration of each of the Department owned gauges in order to establish a reliable correlation among the gauges. This will be used to calculate correlation factors for the gauges.
5. Select gravels from the commission study on aggregate sources (two or three sources for each district) Districts 1,2,3,7 & 10.
6. Select one gauge as the reference gauge. All tests measurements will be made using the reference gauge. The correlation of the gauges will be made using the test measurements and the gauge calibration from No. 4.
7. Obtain permission from University of Arkansas to use the aggregate molds from TRC 70.
8. Mold four or five specimen from each gravel source at different moisture contents and densities using procedures outlined in the TRC 70 report.
9. Calculate the linear regression curve through the data points for each gravel source for the various depths of the probe for wet density and also for moisture content.
10. Derive tables for appropriate gauges from step No. 9 and step No. 4.

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Chapter 1

INTRODUCTION

The Arkansas Highway and Transportation Department has utilized for several years the nuclear method (AHTD 127) as the standard test procedure for determination of density and moisture of foundation materials for highways. However, density measurements by the nuclear gage (Troxler 3411-B) are compared with results from the sand cone test (AHTD 114) for an additional check on moisture/density determination accuracy.

In Southwest Arkansas (Nashville area) results from the nuclear test on gravel bases do not agree with results from the sand cone test. Density readings with the nuclear gage were consistently lower than the sand cone test results, in the range of 5 to 12 pcf. Also, Moisture results from both tests did not agree. Moisture readings with the nuclear gage were generally higher than the oven dry percent of moisture. The major factor contributing to these unreliable nuclear test results was believed to be soil composition.

It is the objective of this study to propose a simple procedure for calibration of the nuclear gage for soils that show soil composition error.

Chapter 2

THEORY REVIEW

NUCLEAR DENSITY MEASUREMENTS

The determination of density by the nuclear method is based upon the attenuation of gamma photon by matter and the detection of those attenuated gamma photons. A gamma photon has no charge or mass, giving it the ability to penetrate deeply into matter. As the photon travels through matter, it collides with the atoms of the material and is randomly scattered. The interaction of gamma photons with matter involves three processes: (1) attenuation by pair production, (2) photoelectric absorption, and (3) Compton scattering.

Attenuation by pair production occurs when the gamma photon has energy of 1.02 MeV and above. However, up to approximately 2.5 MeV, attenuation by pair production is rarely involved in the mechanism of gamma photon scattering in matter. In attenuation by pair production the photon passes through the orbiting electron shell and collides directly with the nucleus of the atom. The photon is reduced to nothing, and a pair of electrons is produced. This pair will consist of one electron with a negative charge and another with a positive charge, a positron.

Radiation sources used in nuclear gages have energies below 1.0 MeV. Hence, attenuation of gamma photons by pair production need not be considered in the analysis of nuclear gages.

Photoelectric absorption occurs when a gamma photon at energy level of 0.1 MeV or less collides with the electron orbiting the nucleus of an atom. With this collision, the gamma photon disappears, transferring all its energy to the electron of the atom. As a result the electron is knocked out of orbit.

Photoelectric absorption is the predominant mechanism of gamma photon absorption at low energy levels, i.e., below 0.1 MeV. There is no absorption of gamma photons above 0.3 Mev.

The probability of photoelectric absorption of the gamma photon is dependent on the chemical composition of the material (Gardner and Kirkham, 1952). Therefore, to decrease the effect of material type on density readings by nuclear gages, low gamma energy sources and detection of gamma photon energy below 0.1 MeV should be avoided.

The Compton scattering is an elastic scattering of the photon upon collision with an electron. The electron will gain energy and will be knocked out of orbit. The gamma photon will continue at a tangent to its original path, with reduced energy. Compton scattering occurs at an energy level between 0.35 and 2.5 MeV.

The nuclear method determines soil density by measuring the scattered gamma photons emitted into the soil from a gamma photon source at an energy level between 0.35 MeV and 2.5 MeV. As gamma photons travel through the soil, some scatter through Compton effect, and some disappear by photoelectric absorption. If a gamma photon detector is placed at a certain distance from the source, the number of photons reaching the detector may be counted. With a constant source, the number of photons reaching the detector depends only on the geometry of the instrument and the absorption capacity of the soil. With a fixed geometry of an instrument, the only variable is the absorption capacity of the soil. This capacity is dependent on the ratio of the atomic number to the atomic weight and on the density of the soil. In soil media, most of the elements have a ratio of the atomic number to the atomic weight of approximately 1/2. Therefore, there is a defined relationship between soil density and the count taken by the detector tube (Ralston and Anday, 1963, p. 17).

The two most common type of radiation counters (or detectors) are the gas filled counters and the scintillation counters. The Geiger-Mueller (GM) counter is a gas filled counting tube with a cylindrical outer shell (cathode) and an axial wire electrode (anode). The GM counter detects the presence of cosmic rays or radioactive substances by means of ionizing particles that penetrate its envelope and set up momentary current pulsations in the gas. The scintillation counter detects and measures ionizing radiation by counting the light flashes (scintillations) caused by radiation impinging on phosphors. A scintillation counter is composed of phosphor, photomultiplier tube, and associated circuits for counting the light emissions produced in the phosphor. An example of a scintillation counter is a thallium-activated sodium crystal optically coupled to a photomultiplier tube, used in conjunction with a single-channel analyzer for energy discrimination.

NUCLEAR MOISTURE MEASUREMENTS

The nuclear method determines moisture content of soil by measuring the slowing of neutrons emitted into the soil from a fast neutron source (1 MeV or more). Neutrons are slowed by elastic collisions with the nuclei of the atoms composing the material being tested. An elastic collision involves the transfer of kinetic energy from the neutron to the nucleus of an atom. As multiple collisions take place, the energy of the neutron is reduced to the point where it is in thermal equilibrium with the molecules of their environment. In this situation, the neutron may gain as much energy as it loses from a collision. In this condition, the neutron is defined as "thermal".

Thermal neutrons possess a spectrum of energies just like normal gas molecules. Their average energy is about 0.025 eV and their speed is about 2200 m per sec at 20C (Troxler, 1963). Once neutrons reach thermal energies they then scatter in accordance with theories of gaseous diffusions until they are captured.

The average energy loss is much greater in neutron collisions with atoms of low atomic weight than in collisions involving heavier atoms. As hydrogen is the only element of low atomic weight in ordinary soils in appreciable amount, it slows fast neutrons more effectively than any other common element present in the soil. Table 2.1 shows how the number of collisions required for neutron thermalization is much less for neutron collisions with hydrogen atoms than with any other element commonly present in the soil. Hydrogen is present in the soil almost entirely in the form of water. Hence, the measure of the resultant cloud of slow or "thermal" neutrons is a function of the soil moisture, whether in the form of the solid, liquid, or vapor state.

Table 2.1 - Relative effectiveness of elements in slowing down fast neutrons (Troxler, 1963, p. 32)

Element	Average Number of Collisions Required for Thermalization	Element	Average Number of Collisions Required for Thermalization
Hydrogen	18.2	Silicon	262
Lithium	69.3	Phosphorus	288
Beryllium	88.1	Sulfur	298
Boron	101.5	Chlorine	329
Carbon	115.4	Potassium	362
Nitrogen	133.5	Calcium	371
Oxygen	152	Titanium	442
Sodium	215	Maganese	506
Magnesium	227	Iron	514
Aluminum	251	Cadmium	1028
		Uranium	2169

The soil moisture content is measured in terms of the number of thermal neutrons counted per unit of time averaged over a volume of soil. Moisture measurement is often expressed as a ratio of the neutron count in the medium of measurement to the count over the same period of time in a primary standard. A primary standard would be, for example, a block of polyethylene where the amount of hydrogen does not vary with time or with change in the environment.

Neutrons are not only slowed by collision with the nucleus of the atoms, but can also be absorbed in these collisions. This may happen in the inelastic scattering process of the neutron. In inelastic scattering the neutron transfers enough of its kinetic energy to the nucleus of the atom to raise the nucleus to a higher state, from which they eventually return, emitting gamma photons (Gardner and Kirkham, 1951). In the inelastic scattering the neutrons are absorbed by the nuclei of the atoms.

The probability of absorption is expressed in the form of the nuclear absorption cross-section. The nuclear absorption cross-section is given in terms of barns, which have units of 10^{-24} cm^{2}. The absorption cross-section is a value established for thermal energies and decreases rapidly with an increase in neutron energy. Table 2.2 shows the absorption cross-section in barns for thermal neutrons of elements found in soils.

For accurate moisture measurements by the nuclear method, neutrons should not be absorbed. Elements that absorb neutrons prevent them from functioning as desired, invalidating the nuclear method.

Table 2.2 - Relative absorption capability of some elements for thermal neutrons (0.025 eV) (Troxler, 1963, p. 31)

Some strong absorbers	Barns	Elements of common encounter	Barns
Rare earths	Some very high, to 46,000		Some very high, to 46,000
Cadmium	2450	Iron	2.53
Boron	755	Potassium	2.07
Indium	196	Nitrogen	1.88
Gold	98.8	Sodium	0.505
Lithium	71.0	Calcium	0.44
Silver	63.0	Hydrogen	0.332
Chlorine	33.6	Aluminum	0.230
		Magnesium	0.063
		Carbon	0.0034
		Sulfur	0.00052
		Oxygen	0.0002
		Phosphorus	0.0002
		Silicon	0.00016

Of the major neutron absorbers, the only ones that might have to be taken into consideration in normal soil research and calibration are boron, lithium, chlorine, and perhaps cadmium (Troxler, 1963).

NUCLEAR GAGE CONFIGURATION

There are three types of source to detector configuration used in nuclear gages. They are (1) the direct-transmission, (2) the backscatter, and (3) the air-gap configuration.

In the direct-transmission configuration the radiation source is inserted into the soil and transmits gamma rays in all directions (Figure 2.1). The majority of the gamma rays counted have traveled in a relatively straight line from the source to the detector.

Factors that affect the direct-transmission technique are soil type, disturbance of soil by insertion of the

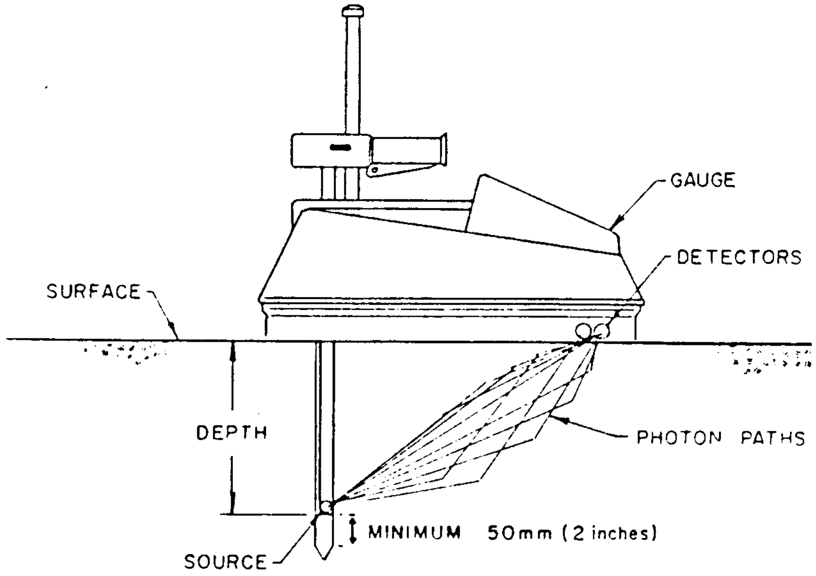

Figure 2.1 - Direct transmission density geometry

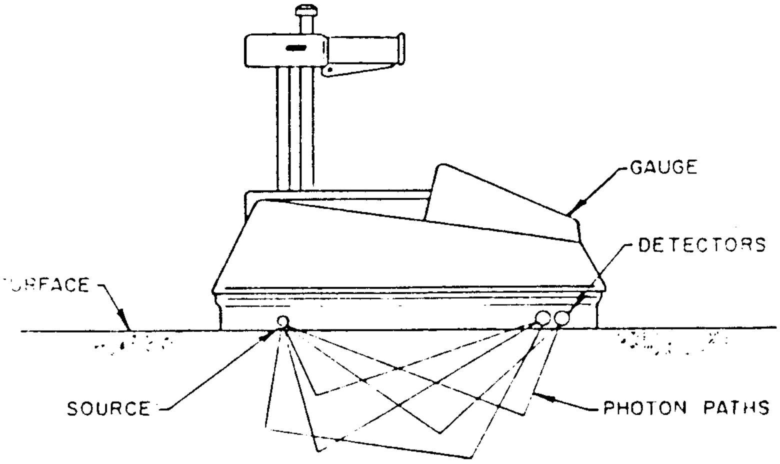

Figure 2.2 - Backscatter density geometry

probe and variation in the path length between the source and the detector.

In the backscatter configuration the radiation source is positioned at the surface of the soil (Figure 2.2). Rays reflected or scattered back by interaction with the electrons of the soil mass are detected and counted.

The principal criticism of the backscatter technique is that the measured radiation is not distributed uniformly through the compacted layer. Most of the radiation is scattered back from a top thin layer. Surface roughness and soil type are major factors affecting the backscatter technique.

The air-gap technique consists of taking a gage response in the usual backscatter position and then raising the gage to a fixed height above the soil surface where a second response is taken. A nomograph can be obtained that gives density independent of sample composition as a function of the normal flush response and gap response. A more detailed explanation on the air-gap technique is given in the next section (Historical Development).

The material to be tested will frequently govern the type of gage configuration to be preferred. Where it is reasonably simple to drive or drill the required hole without significant disturbance of the material around the hole, the direct transmission offers great accuracy and control of depth of test. When density measurements are less than about 3 inches in depth or when it is not practicable or desirable to disturb the test material, the air-gap and backscatter methods are used. The air-gap method shows a slight superiority in accuracy to the backscatter method.

HISTORICAL DEVELOPMENT

The initial use of gamma rays for soil investigation was applied in the early 1940's by geologists and geophysicists in petroleum explorations. As early as 1941, a paper by Pontecorvo described the basic process used in the nuclear method today. Engineers became interested in the potential of using radioactivity to measure soil density and moisture shortly after World War II.

In 1950, Belcher, Cuykendall, and Sack (according to Smith et al, 1968), at Cornell University, initiated research on determining soil moisture and density by a subsurface-type neutron and gamma ray scattering instrument.

In 1952, Belcher et al (according to Smith et al, 1968) reported on the first surface-type instrument applying nuclear methods for measuring soil moisture and density in thin layers of soil. At the same time, Gardner and Kirkham (1952) stated the principles on which neutron scattering for soil moisture determination was based.

One of the earliest reports by the Highway Research Board describing field measurements of soil moisture and density was done by Horonjeff and Goldberg (1953). The report showed that the moisture and density measurements by nuclear methods were reproducible and consistent. However, the results were in error of as much as 25 percent when compared to conventional methods in the top 2-3 ft surface layer.

The first work using scintillation detection was done by Bernhard and Chasek in 1955 (according to Shunil, 1957).

In 1953, Nuclear-Chicago Corporation was asked by the Civil Aeronautics Administration to design a portable field electronic unit to be compatible with Cornell University moisture and density probes. The project was never completed. However, in 1955, the project was revived by the U.S. Army Corps of Engineers, Ohio River Division. This time, Nuclear-Chicago Corporation was asked to design a field depth density and moisture system which would be tested and calibrated by the Corps.

After completion of the contract with the Corps, Nuclear-Chicago Corporation continued its development to improve the depth system. It also started a new project, surface moisture and density measuring equipment.

By 1960, Nuclear-Chicago had a complete density/moisture (d/M) nuclear gage system commercially available. The d/M gage system consisted of an electronic scaler or read-out, plus four separate gages : depth density and moisture units, and surface density and moisture gages.

The feasibility of nuclear methods of soil moisture and density analysis was clearly established by researchers in the 1950's. As commercial nuclear gages reached the market, state highway departments began to consider them for possible use in their construction testing. The decade of the 60's was the period of field evaluation of the first nuclear gages.

In 1959, the AASHTO Road staff prepared a program that could be used by any agency for evaluation of the nuclear moisture-density testing equipment (Carey, Shook, and Reynolds, 1960).

The immediate obvious advantages of the nuclear method were nondestructiveness, measurement speed, and reproducibility. However, in the early 60's, when the nuclear gages were used in the field and compared to the existing gravimetric methods, discrepancies between results occurred. The question of accuracy of nuclear devices arose.

Carlton, in 1960, reported on field density and moisture test results with the first nuclear gage designed by Nuclear-Chicago Corporation.

Carlton used a single density calibration curve for two different material types, lean clay subgrade and a coarse granular base. Density test results indicated a precision of ± 2.8 pcf. Again, a single moisture calibration curve was used for the two different material types. Moisture test results indicated a precision of ± 0.9 lb of water per cu ft. Carlton concluded that effect of material type had no significant influence on the calibration of either the moisture or density.

Gnaedinger (1960) also described experiences with the first Nuclear-Chicago d/M gage, including correlation data