The neutronic method for measuring the water content of soils is more and more used by agronomists, hydrologists and pedologists. On the other hand, the studies on the phenomena of slowing down and diffusion process have shown a narrow relation between the thermal absorption ($E_0$) and diffusion ($E_2$) constants and the thermal flux developed in the soil around a fast neutron source like Am-Be. Then, the authors present two original realizations of the direct measurement of $E_0$ and $E_2$.

The method described consists in the measurement, in a cube of graphite with a Am-Be source in the middle, on one side of the perturbation of the thermal flux, obtained by the introduction of 300 g of soil, and on the other side of the transmitted thermal flux measured through the same sample of soil, on a side of the cube.

After calibrating the device, these two parameters give $E_0$ and $E_2$ which are easily introduced in the calibration equation of neutron moisture gauge. Also these two values are useful for the pedologists because $E_0$ is connected to clay content in the soil and $E_2$ is connected to the type of clay by the way of rare earth contents.

(Key words : thermal neutron constants, soil, neutron moisture gauge, calibration, pedology)

Introduction

For the soils and rocks, the use of the principles and experiments related to the neutron diffusion is now well established seeing that in 1953, Brumberger proposed the first time the neutronic measurement of soil water. Then a great diversification took place on one hand in the field of studies which range from geology to agronomy, on the other hand with regards to the neutronic techniques which -anges from the life time of neutron to neutronography. But undoubtedly, the methods derived from the measurement of fast, epithermal and thermal flux measured through the soil, are rarely employed with thermal flux that are in situ measured. The description of its principles made with the aid of the previous nuclear reactor studies.

Then it is paradoxal to observe that the neutronic method was accepted by soil physicists with great difficulty. This is an example that, still 30 years of its introduction, the neutronic measurement of soil water content is not very conveniently calibrated. It is unnecessary to seek the reason for this difficulty in a nonexistent technological complexity in measuring thermal flux. On the other hand, it evidently appears that the main hindrance is the heterogeneity of the chemical composition of soils and rocks. To face this problem the researcher attempted to determine for each medium the relation between the measured flux and the desired variable (soil water content or rock porosity). Although it allows to give a response for the studied case, this approach was quickly recognized as unable to give a generalization of the results and consequently to calibrate neutron moisture meters. With the intent to answer this so put question, we have proposed the direct measurement of neutronic parameters of dry soils and rocks samples. This approach on the other side of previous methods, in very useful not only to solve the calibration of neutron moisture meters but also to give new means to characterize soils and rocks.

1. The neutronic soil constants.

In connection with neutronic constants, it is usual to distinguish the main elements, hydrogen and the trace elements. Outside oxygen, the fundamental constituent elements are silicon, aluminium, iron, titanium and manganese; they are expressed by their respective oxides. Hydrogen, important element because this neutronic properties, is present as constituent mineral water or hydroxil ions. We can measure it by its equivalent water obtained by an oxidation at 1000°C during one hour and called here by extension constituent water. This there is a relation between this constituent water and the 100% percentage for several different soils. The elements as trace elements and neutronically important are essentially boron, lithium and certain rare earths like samarium, gadolinium, europium. We should be remember that their analysis is delicate and very imprecise compared with their great interaction with the neutrons.

In connection with neutronic constants, it is possible to separate neutron slowing down, thermalization and thermal diffusion. On the other hand in order to take into account particular neutronic properties of soil hydrogen, we study these constants with using this element as a variable.

The slowing down process being defined by the slowing down power $E_0$ and the fast transport neutron cross section, we can show that the soil water is the main parameter for the slowing-down and that the others soil elements, nearly exclusively the major ones, arise...
The thermalization stage can be ignored without error in this type of soil neutronic measurement. During the thermal diffusion process, the water remains a narrow section for several soils between $I_3$ and the constitutive water. On the other hand thermal absorption is strongly dependent on the amount of trace elements particularly (boron) and there is no relation between $I_3$ absorption parameter and soil constitutive water (fig. 3).

![Fig. 1 - Fast transport neutron cross section (cm$^2$/g) versus constitutive soil water content](image1)

![Fig. 2 - Thermal diffusion (cm$^2$/g) versus soil water content](image2)

![Fig. 3 - Thermal absorption (cm$^2$/g) versus soil water content](image3)

Thus we have determined the absorption cross section of several dry ($105°C$ during 24 h) soils; the measurement is taken by comparing with a soil sample which is the main constitutive part of soil. With this measurement, we observe on one hand a systematic discrepancy between the values measured and calculated from the known chemical composition, which does mean that the trace elements are badly known to be used to calculate thermal neutron diffusion; on the other hand we note the lack of relation between $I_3$ and $I_4$.

Such a measurement of neutronic constants is long and expensive; thus a new method is proposed. It requires a graphite pile of the same kind as the BOREAL device: a thermal neutron flux arises in the pile from an several curies $A$ source. A thermal flux detector measures the perturbation introduced by a soil sample placed between the detector and the source. Another detector measures on a side of the pile the thermal neutron beam transmitted through the same soil sample. We obtain two count rates depending on $I_3$ and $I_4$ and we calculate from these after a previous calibration, the thermal neutron soil constants.

3. The calibration of neutron moisture meter.

We have seen that soils and rocks have, because of their chemical composition, a great variety of neutron behaviour which can be seen in the large range of $I_3$ and $I_4$. This has a direct consequence on the neutron moisture gauges the principle of which consists of relating the measurement of a thermal flux around a fast neutron source, introduced with a tube in the soil, to the water content of this soil. The so obtained relation is not unique and depends on the chemical composition and the bulk density of soil. This is moreover shown by classical experimental calibration which gives the correlation between a water content measured by burning the soil at $105°C$ during 24 h and the count rate: from one soil to another the calibration curve that can be considered as straight lines for classical devices have a slope which have a 40% range, and the absolute measurement is obtained with an accuracy of ten volumetric points (pure water represents 100 volumetric points and a saturated soil 40 volumetric points).

A solution was proposed which consisted in determining the calibration curve from a model describing the slowing down and the thermal diffusion by soil chemical composition. A standard method to measure the thermal absorption of any sample (method not still used for the soils consist in introducing the sample in an equilibrium nuclear reactor and to move periodically sample. We measure in a certain point the neutron flux modulation spreading in the whole reactor with the assistance of an ionization chamber. The fundamental of the signal is proportional to sample absorption: this is the amplitude oscillation method. The phase oscillation method is based on the fact that an oscillatory source gives in a nuclear reactor simultaneously a neutron flux spreading everywhere and a perturbation measurable only near the sample. By judiciously putting the detector, we show that the length of phase between the retained signals with two samples of different exposure is proportional to the difference of neutron absorption cross section.

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The calculated calibration curve be obtained with an accuracy of 12.5%.

The theory shows, however, that it is possible to write the count rate of the neutronic gauge under the form:

\[ N = (\alpha \cdot \phi + \beta) \mu_0 + \gamma_0 \delta \]  

where \( \mu_0 \) is volumetric moisture \( \rho_0 \), bulk density; \( \beta, \gamma \) and \( \delta \), specific constants of the soil depending upon the chemical composition; \( \alpha \) and \( \beta \) define the slope curve and \( \gamma \) and \( \delta \), its origin ordinate. This representation besides enables to notice on fig.4 that, when we pass from a clay soil (small percentage of SiO\textsubscript{2}) to a sandy soil, the \( \phi_0 \) influence on the slope of calibration \( \phi_0 \) increases; whereas, the \( \mu_0 \) influence on origin ordinate decreases; on the other hand we notice that the correlation between SiO\textsubscript{2} and the calibration curve is very large, which excludes the calibration from knowledge of only major elements.


Besides the calibration of neutron moisture gauges, the \( \phi_0 \) and \( \mu_0 \) measurement gives to hydrogeologists an information about the neutronic homogeneity of the soil at the scale of an experimental agricultural soil or a watershed. We remark that the soil is more depth homogeneous than could be predicted by chemical analysis; this is a favorable point for the using of neutron moisture gauges. In the case of the sandy loam soil of Cadarache, taken as example, we could note that the dispersion of \( \phi_0 \) is not more than four percent on all the cultivated plot. On the other hand we often observe an increase of \( \phi_0 \) near the soil surface which can reach twenty-five percent and is perhaps derived from trace elements in the soil. These results were corroborated by activation analysis.

This relation between soil chemical composition, and neutronic constants gave on the idea of exploiting the \( \phi_0 = f (\mu_0) \) diagram. On the figure 5 we observe that the image-points are not randomly distributed; they are brought together in relation to the sample sites. It is possible easily to distinguish on this diagram a soil of Bouaké from a soil of Nancy. These collections are representative of the granulometry and and the parameters of calibration curve. If \( \phi_0 \) varies in the range of 10\textsuperscript{2}, the slope \( \phi_0 \) varies in the range of 4\textsuperscript{2} and the absolute measurement of volumetric content of 4\textsuperscript{2} to 30 volumetric points; in the case of \( \mu_0 \), for a variation of 10\textsuperscript{2}, the variations are respectively of 10\textsuperscript{2} and 10\textsuperscript{3}. Then, by the direct measurement method the precision obtained on the calibration curve are of respectively + 1.22 for \( \phi_0 \) and 1.22 for absolute values due to \( \phi_0 \) and 0.622 for \( \mu_0 \) and 3.42 for absolute water contents due to \( \mu_0 \).

![Fig.4 - Neutron moisture gauge calibration curve parameters (\( \phi_0 \), \( \phi_1 \) - \( \phi_2 \) - \( \phi_3 \)) versus percentage of SiO\textsubscript{2}.](image)

![Fig.5 - Neutronic characterization of soils with \( \phi_0 \) versus \( \mu_0 \).](image)
mineralogy of the soil; for example, we can see that a soil obtained with great \( I_d \) and small \( I_a \) will be richer in clay than a soil with small \( I_d \) and great \( I_a \). Generally, it is possible to detect a tendency when the increase of \( I_d \) is followed by an increase of \( I_a \) and means that we pass from a sandy soil to a clayey one; this tendency is the reflexion of the granulometry and mineralogy variation.

On the other hand, if we observe in an accurate manner a site, it is possible to see that the obtained points are on a straight line. This is the case, for example, with Tillabery and Tarascon soil; we then say that these points correspond to two soils which are mineralogically different; the excursion on this straight line is only dependent on granulometry. Thus if we obtain a narrow correlation between \( I_a \) and \( I_d \) for a group of points, these points are representative of a same mineralogic soil. In addition let us consider the point obtained for a \( I_d \) value which correspond to the diffusion of waterless soil (see Fig.1): the \( I_a \) value of this point is representative of the clayless part of soil and give us an information on this part; for example, we distinguish between ferrallitic soil (Boulaki) and siliceous soil (Grenoble). Figure 6 shows that is is possible, in certain cases, to consider the \( I_a \) as composed of two granulometric parts: the first one \(< 20 \mu m (I_{a1}) \) and the sandy one \((I_{a2})\). Thus the excursion of the \( I_a = f (I_d) \) curve is significative of the \(< 20 \mu m \) variation. Finally, because the variation of \( I_d \) depends upon constitutive water we can say that the different variation of \( I_a (I_{a2}) \) with relation to \( I_d (I_{a1}) \) would be related with the type of (kaolinite, montmorillonite,...).

**Conclusion**

The direct measurement of \( I_a \) and \( I_d \) soil parameters allows the interpretation of the obtained results by thermal flux near a fast neutron source introduced in the soil. We have shown that this measurement allows one to have an adequate neutron moisture gauges calibration. A simple measuring device with a graphite pile is presented.

Besides the neutron humidimeter calibration, we show the profit it is possible to obtain from the neutron soil characterization also to assess their neutronic heterogeneity on an experimental plot (using of neutron humidimeter) also to obtain a quick classification of a soil useful for the pedologist in a \( I_a = f (I_d) \) diagram.

We have only stressed one of the important aspects of direct neutronic applications in the field of the problems set by hydrologists or pedologists. We have also to quote as an example the "in situ" determination of the slope of calibration curve of neutron moisture gauges by a double measurement of thermal and epithermal fluxes; in the same manner, we can cite the use of neutronography for non destructive evaluation of the space-time evolution of roots. Then the gamma-neutron method, from a device with a Thallium source and a thermal neutron detector, was used to measure the D2O content in the soil water and to know dispersion movement.

As can be seen, the agronomist as the pedologist can expect numerous services from neutronic method. We have here some new technics at this crossing of the agronomy and the neutronic method that could be called "Neutronoagronomy".

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