

THE MEASUREMENT OF THERMAL NEUTRON CONSTANTS OF THE SOIL ;

APPLICATION TO THE CALIBRATION OF NEUTRON MOISTURE GAUGES AND TO THE PEDOLOGICAL STUDY OF SOIL

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The neutronic method for measuring the water content of soils is more and more used by agronomists, hydrogeologists 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 ( $I_0$ ) and diffusion ( $I_d$ ) constant and the thermal flux developed in the soil around a fast neutron source like Am-Be. Then, the authors present two original applications of the direct measurement of  $I_0$  and  $I_d$ .

The method described consists in the measurement, in a cube of graphite with an 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  $I_0$  and  $I_d$  which are easily introduced in the calibration equation of neutron moisture gauge. Also these two values are useful for the pedologists because  $I_d$  is connected to clay content in the soil and  $I_0$  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 1925 Brummer for the first time proposed the neutronic measurement of soil water. Then a great diversification took place on one hand in the field of study which ranges from geology to agronomy, on the other hand with regards to the neutronic techniques which ranges from the life time of neutron to neutronography. But undoubtedly the methods derived from the measurement of fast, epithermal and thermal flux developed around a fast neutron source in the soil is by far the most interesting ; it is especially employed with thermal flux that are easily measured<sup>1</sup>. 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 after its introduction, the neutronic measurement of soil water content is not very conveniently calibrated<sup>2</sup>. 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. 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 intrinsic

neutronic parameters of dry soils and rocks samples. This approach on the other side of previous methods, is 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 the chemical composition of soils and rocks, 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 hydroxyl ions. We can measure it by its equivalent water obtained by an oxydation at 1000°C during one hour and called here by extension constituent water. This there is a relation between this constituent water and the SiO<sub>2</sub> percentage for several different soils. The elements as trace elements and neutronicly 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  $I_0$  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

in the fast transport definition (fig.1) with the second order. The thermalization stage can be ignored without error in this type of soil neutronic measurement. During the thermal diffusion process, the water remains the predominant term concerning the  $L_d$  diffusion parameter, the major elements essentially arising by the  $SiO_2$ . Then we observe, as showed on figure 2, a narrow relation for several soils between  $L_d$  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  $L_a$  absorption parameter and soil constitutive water (fig.3).

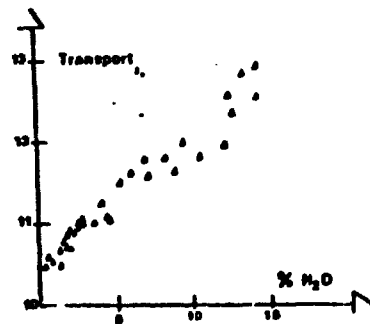


Fig.1 - Fast transport neutron cross section ( $cm^2/g$ ) versus constitutive soil water content

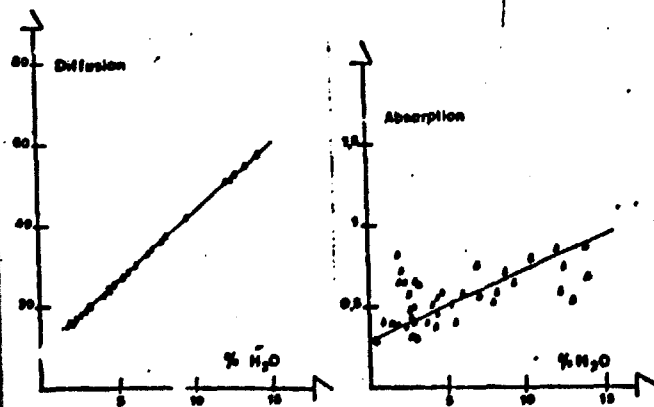


Fig.2 - Thermal diffusion ( $cm^2/g$ ) versus soil water content.  
 .3 - Thermal absorption ( $cm^2/g$ ) versus soil water content.

Then it appears from this consideration that, neutronically, a soil could be well defined for the slowing down and thermal diffusion if we know the constitutive water content and the trace elements. The accuracy of this definition is given by that of the correlation which exists between constitutive water and fast transport. Then we can turn over the proposition and, that is an important point, we can say that the knowledge of  $L_a$  and  $L_d$  is sufficient to neutronically define the soil if we are interested in the measurement of thermal flux which arises around a fast neutron source; the accuracy of the assessment thus established will be connected to variability of the influence on the fast transport of the constitutive water, influence balanced by the relation between fast neutron flux and fast transport.

## 2. The measurement of thermal diffusion constants $L_a$ and $L_d$ in the soil; and rocks.

A standard method to measure the thermal absorption of any sample (method non 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 neutronic 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 sample gives in a nuclear reactor simultaneously a modulation spreading everywhere and a perturbation measurable only near the sample. By judiciously putting the detector, we show that the lock of phase between the obtained signals with two samples of different capture is proportional to the difference of neutron absorption cross section<sup>3</sup>.

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 silice 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  $L_a$  and  $L_d$ .

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<sup>4</sup>; a thermal neutron flux arises in the pile from an several curies Am-Be 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 dependly on  $L_a$  and  $L_d$  and we calculate from these after a previous calibration, the thermal neutronic 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 neutronic behaviour which can be seen in the large range of  $L_a$  and  $L_d$ . 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<sup>5</sup>. 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 curves 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<sup>6,7</sup>. As a matter of fact, this method is advantageous, compared with merely experimental calibration, for the interpretation and the extent of results; the error of determination from the calculation of the neutronic constants, of soils

gives 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 :

$N = (\alpha \rho_v + \beta) \rho_d + \gamma \rho_d + \delta$  where  $\rho_v$  is volumetric moisture,  $\rho_d$  bulk density,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$  specific constants of the soil depending upon the chemical composition;  $\alpha$  and  $\beta$  define the slope's 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  $SiO_2$ ) to a sandy soil, the  $\rho_d$  influence on the slope of calibration ( $\alpha$ ) increases; whereas, the  $\rho_d$  influence on origin ordinate decreases; on the other hand we notice that the correlation between  $SiO_2$  and the calibration curve is very large, which excludes the calibration from knowledge of only major elements.

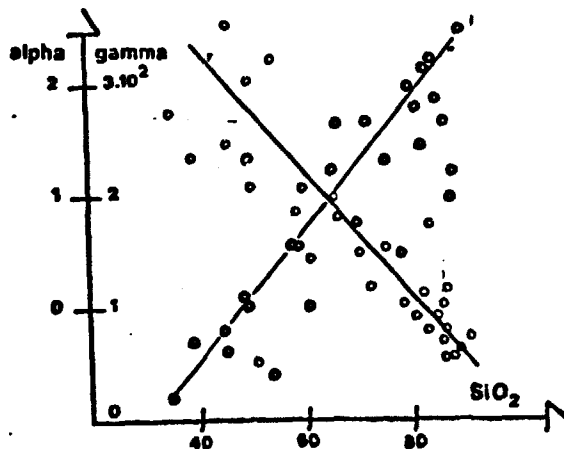


Fig. 4 - Neutron moisture gauge calibration curve parameters ( $\alpha$ ,  $\odot$  -  $\beta$ ,  $\bullet$ ) versus percentage of  $SiO_2$ .

Because the  $I_a$  and  $I_d$  define entirely the slowing down and thermal diffusion, except on the second order fast transport, the thermal flux is also itself entirely defined and consequently,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$  parameters. We have calculated the variation of  $\alpha$  versus  $I_a$  and  $I_d$  for a matrix of sandy soil with consecutively added type absorber (Cadmium) and added constitutive water. We observe, according to the published calibration curves, that the influence on the slope decreases in the same manner when the soil has a larger clay content water v constitutive water content and traces elements. With using all the correlations between  $I_a$ ,  $I_d$  and  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$  in a large range of soils, we notice that the fast transport imprecision has a small influence on the obtained calibration curve. Then the  $I_a$  and  $I_d$  values entirely define the soil calibration curve by giving univocally  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ .

Therefore the proposed calibration method is the following: on a 300 g soil sample, we measure with graphite pile,  $I_a$  and  $I_d$ . A small computer program give  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$ . The thermal diffusion is directly given by  $I_a$  and  $I_d$ ; the slowing down, is obtained from the constitutive water content issued from  $I_d$  and we improve the accuracy by using for  $I_{tr}$  the values of several reference soils distributed from the constitutive water. Calcareous soil is treated separately for the  $CO_2Ca$  content above ten percent. The accuracy of obtained calibration curve is directly related to that of  $I_a$  and  $I_d$ . The influence on the calibration curves passes through the relation between this two constants

and the parameters of calibration curve. If  $I_a$  varies in the range of 10% the slope  $\alpha$  varies in the range of 4% and the absolute measurement of volumetric content of 4% to 30 volumetric points; in the case of  $I_d$ , for a variation of 10%, the variations are respectively of 1% and 10%. Then, by the direct measurement method the precision obtained on the calibration curve are of respectively  $\pm 1,2\%$  for  $\alpha$  and  $\pm 1,2\%$  for absolute values due to  $I_a$  and  $\pm 0,68\%$  for  $\alpha$  and  $\pm 3,4\%$  for absolute water contents due to  $I_d$ .

#### 4. Neutronic soil characterization.

Besides the calibration of neutron moisture gauges, the  $I_a$  and  $I_d$  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  $I_a$  is not more than four percent on all the cultivated plot. On the other hand we often observe an increase of  $I_a$  near the soil surface which can be 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  $I_a = f(I_d)$  diagram. On the figure 5 we observe that the image-points are not randomly distributed; they are brought together in relation to the sample site. 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

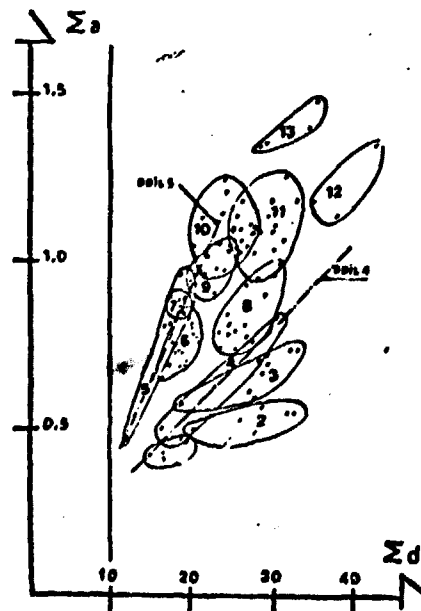


Fig. 5 - Neutronic characterization of soils with  $I_a$  versus  $I_d$ .

Origin of soils: Ivory Coast (1 Adlopodoum, 2 Cagnoa, 3 Bouaké), Niger (4 Tillabery), France (5 Tarascon, 6 Cadarache, 8 Lunel, 9 Crenoble, 10 Lézize, 13 Nancy), Belgium (7 Gembloux), Algeria (11 El Khemis), Tunisia (12 Ben Kasseur).

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 reflection 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 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 ferralitic soil (Bouaké) and siliceous soil (Grenoble). Figure 6 shows

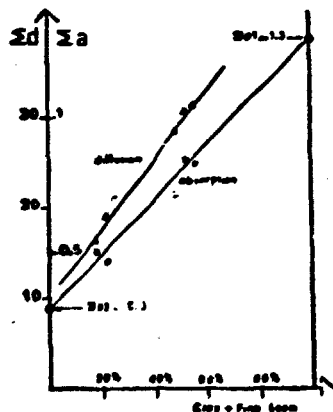


Fig. 6 - Diffusion and absorption cross sections of soil n°4 Tillabery versus clay + fine loam (< 20  $\mu$ m) percentage.

that it is possible, in certain cases, to consider the soil as composed of two granulometric parts : the red one < 20  $\mu$ m ( $I_{d1}$ ,  $I_{a1}$ ) and the sandy one ( $I_{d2}$ ,  $I_{a2}$ ). Thus the excursion on 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  $I_a$  ( $\Delta I_a$ ) with relation to  $I_d$  ( $\Delta I_d$ ) 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 also ensures 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 neutronic 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  $D_2O$  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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