SENSITIVITY AND ACCURACY OF THE ROENTGENOSCOPIC METHOD OF DETERMINING MOISTURE CONTENT IN A POROUS BODY

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Optimal conditions are determined for roentgenoscopic determination of local moisture content in a porous body.

It is known from the theory of interaction of hard electromagnetic radiation with matter [1-4] that in the γ ray region with photon energies of the order of 1 MeV, the mass attenuation coefficients of all the light elements ($Z < 30$) are the same in the first approximation. The gammascopic method of moisture content determination is based on this fact [5]. In the x ray range (quantum energies of the order of tens of keV) the mass attenuation coefficients differ even for the light elements. It is of great practical importance that these coefficients for the x ray range are very much greater than for γ radiation.

In accordance with Bouguer's law the attenuation of a parallel monochromatic x ray beam by a moist porous body is described by the formula

$$I = I_1 \exp\left[-(\mu_0\rho_0 + \mu\rho)\, l\right]. \quad (1)$$

Considering that

$$I_0 = I_1 \exp(-\mu_0\rho_0 l), \quad (2)$$

we find

$$\rho = (\mu l)^{-1} \ln (I_0/I), \quad (3)$$

$$u = \rho/\rho_0 = (\mu l \rho_0)^{-1} \ln (I_0/I). \quad (4)$$

In the experimental process the value $L = \ln (I_0/I)$ is measured, which, as is evident from Eq. (3), equals

$$L = \mu l \rho.$$

The sensitivity of the method is determined by the ratio

$$S = \frac{dL}{d\rho} = \mu l. \quad (5)$$

From Eq. (5) it is evident that the sensitivity is proportional to the specimen thickness and the coefficient μ. The latter decreases with increase in photon energy. It is to be understood that it does not follow from this that the photon energy can be decreased to the lowest value possible in the device, and the specimen thickness chosen unproportionally large, since this would decrease the values I and I_0 and measurement error would increase. We will attempt to evaluate this error.

From Eq. (3) it follows that

$$\sigma_\rho = \rho_0\sigma_u = \frac{\sigma_L}{\mu l} = \frac{1}{\mu l}\sqrt{\frac{\sigma_{I0}^2}{I_0^2} + \frac{\sigma_I^2}{I^2}}\,. \quad (6)$$

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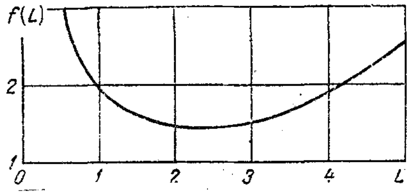

Fig. 1. The function f(L).

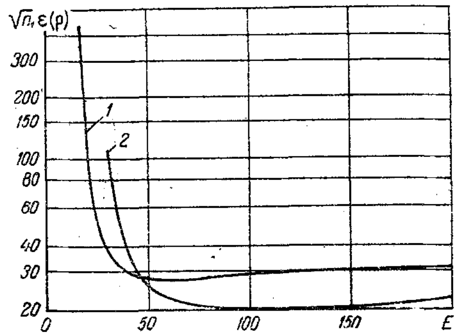

Fig. 2. $\sqrt{n_1}\varepsilon_\rho$ as a function of photon energy (E, keV) for various specimen thicknesses: 1) l = 2 cm; 2) l = 4 cm.

Having statistical material for determination of the terms in the radicand in Eq. (6), it is possible to determine the standard deviation of the quantity measured. In our experiments the values σ_{I0}/I_0 and σ_I/I were 1 to 2%. Calculation by Eq. (6) for $\mu = 0.30$ cm^2 g^{-1} (H_2O, E = 35 keV) and $l = 3.5$ cm gives $\sigma_\rho \le 0.027$ gcm^{-3}.

We will perform a theoretical evaluation of the optimum measurement conditions for several possible cases.

In accordance with [6]

$$\sigma_{I0}/I_0 = (n_0\eta)^{-1/2}, \quad \sigma_I/I = (n\eta)^{-1/2}.$$

Using Eq. (6), we obtain

$$\sigma_\rho = \frac{1}{\mu l}\sqrt{\frac{1}{\eta}\left(\frac{1}{n_0}+\frac{1}{n}\right)}. \tag{7}$$

Taking the attenuation law in the form

$$n = n_0 \exp(-\mu l \rho),$$

we rewrite Eq. (5) in the following manner:

$$\sigma_\rho = \rho_0\sigma_u = \frac{\sqrt{1+\exp(\mu l \rho)}}{\mu l\sqrt{\eta n_0}}. \tag{8}$$

From Eq. (8) it is evident that the quantity σ_ρ has its smallest value at $\rho = 0$, however the standard deviation then tends to infinity.

From Eq. (8) it follows that

$$\varepsilon_\rho = \frac{\sigma_\rho}{\rho} = \frac{\sigma_u}{u} = \varepsilon_u = \frac{\sqrt{1+\exp(\mu l \rho)}}{\mu l \rho\sqrt{\eta n_0}}. \tag{9}$$

For selection of an operating mode under conditions where the value of $L = \mu l \rho$ varies over a narrow range about some mean value during measurement, it is useful to determine at what L value the function

$$f(L) = L^{-1}\sqrt{1+\exp L} \tag{10}$$

has a minimum, which point, obviously, coincides with the minimum of Eq. (9) for ηn_0 = const. As may easily be seen, determination of this minimum reduces to solution of the transcendental equation $\exp L = 2/L - 2$ the root of which is approximately 2.22. The graph of Eq. (10) is presented in Fig. 1, from which it is evident that the optimum conditions for this case occur at $1.5 \le L \le 3$.

Two factors were not considered in our evaluation: first, the dependence of radiation detector efficiency on photon energy, and second, the attenuation effect of the solid skeleton of the body and the structural walls of the apparatus. As may be seen from the tables presented in [7], for NaI scintillation crystals 25 and 40 mm in thickness, as used in our apparatus, the efficiency $\eta = 1$ at photon energies of 0 to

TABLE 1. Optimum Specimen Thickness versus Photon Energy for Quartz Sand (SiO_2, 1.8 g/cm^3) and Water (H_2O, 0.2 g/cm^3)

Photon energy, E, keV	Optimum specimen thickness, l_m, cm
20	0,44
30	1,25
40	2,32
50	3,44
60	4,27
80	5,44
100	6,39
150	7,45
200	8,30

150 keV, i.e., practically over the entire x ray wavelength range. It follows from this that use of scintillation methods in roentgenoscopic studies is very efficient, and counter efficiency as a function of quantum energy need not be considered.

The effect of radiation absorption by the solid skeleton of the specimen, and sometimes by the apparatus walls, may be quite significant, if the radiation power at the tube output is rather limited, for example, when using diffractometric devices for roentgenoscopy. It should, however, be noted that consideration of these factors in the x ray range is quite complicated.

In fact, if we neglect attenuation of the beam by structural walls, which in principle can be constructed to have an insignificant effect on intensity, we may assume that in accordance with Eq. (2)

$$n_1 = n_0 \exp(\mu_0 \rho_0 l).$$

From Eq. (9) at $\eta = 1$ we obtain

$$\sqrt{n_1}\varepsilon_\rho = (\mu l \rho)^{-1} \exp(0.5\mu_0 l \rho_0)\sqrt{1 + \exp(\mu l \rho)}\,. \tag{11}$$

In the gamma ray region, where $\mu_0 \cong \mu$, the criteria for the optimum measurement mode are found comparatively simply [5]. For the x ray range, in each concrete case the optimum regime must be selected by trial and error. The curves of Fig. 2 show the character of the dependence of the quantity expressed by Eq. (11) on photon energy for two different values of specimen thickness l, under the condition that $\rho = 0.2$ gcm^{-3}, $\rho_0 = 1.8$ gcm^{-3}, and the mass attenuation coefficients μ and μ_0 correspond to H_2O and SiO_2.

Sometimes the choice of an optimum mode may be simplified with the aid of the relatively simple solution of the problem of finding an optimum specimen thickness l for constant radiation quantum energy and given moisture content. It is simple to prove that determination of a minimum for Eq. (11) for constant ρ, ρ_0, μ, and μ_0 reduces to finding the root of the following transcendental equation:

$$\frac{2}{\mu l_m \rho} - \frac{\mu_0 \rho_0}{\mu \rho} = \frac{1}{1 + \exp(-\mu l_m \rho)}\,. \tag{12}$$

Equation (12) is solved for l_m relatively simply by the method of successive approximation. To calculate the first approximation, the exponential function in the denominator of the righthand side is taken equal to unity, and the equation obtained is solved for l_m. The righthand side of the equation for the second approximation is obtained by substitution of the l_m value obtained in the first approximation, etc.

Table 1 presents l_m as a function of photon energy for material of the following composition as the specimen: SiO_2, $\rho_0 = 1.8$ gcm^{-3}; H_2O, $\rho = 0.2$ gcm^{-3}. The values of μ and μ_0 for the various energy values were taken from the tables of [8].

NOTATION

I, I_0	are the intensity of radiation which has traversed through layer of moist specimen, and through layer of same specimen containing no moisture;
I_1	is the intensity of radiation incident on specimen;
n, n_0, n_1	are the number of photons corresponding to these intensities incident on radiation detector input over identical count period;
ρ_0 and ρ	are the density of solid skeleton and absorbed moisture (mass per unit volume);
μ_0 and μ	are the mass attenuation coefficients corresponding to these two phases;
l	is the beam path in specimen (specimen thickness);
u	is the relative specific moisture content;
L	is the signal level;
S	is the sensitivity of roentgenoscopic method;
σ_x	is the standard deviation of quantity;
ε_x	is the relative standard deviation of quantity x;
η	is the detector efficiency;
E	is the photon energy;
l_m	is the optimum specimen thickness at given photon energy and moisture content;
Z	is the atomic number of element.

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