THERMAL-IR EMISSIVITY OF SOILS AND ITS DEPENDENCE ON POROSITY, SURFACE ROUGHNESS AND SOIL-MOISTURE

Sune R J Axelsson
Linköping University
Sweden

VII/3:127

ABSTRACT

Experimental results are presented on the emissivity of soils in the 9.5-11.5μm wavelength interval. In particular, the dependence on water-content, porosity and surface roughness was studied. The results show that soil-moisture increases the emissivity of sand from 0.90 for dry sand to 0.94-0.96 at high water contents. Most of the emissivity change occurs when the water-content exceeds ten per cent. Comparative measurements in the 0.50-0.62 μm wavelength interval show that the reflectance is affected at much lower soil-moisture levels. For fine-grain soils, emissivities in the range 0.94-0.97 were measured with weaker soil-moisture response than for sand. It was also shown that variations in porosity and surface roughness changed the soil-emissivity one or two per cent

1. INTRODUCTION

Objects in nature are not perfect black-body radiators, which reduces the accuracy of IR-thermographic measurements. An uncertainty in emissivity of five per cent, for instance, will introduce errors in the estimated surface temperature on the order of 2-3 °C. The accuracy can be highly improved, however, if the emissivity of the ground is known or can be predicted from available information on the surface conditions.

The emissivities of soils have earlier been studied by several investigators e.g. [1] - [5]. Buettner and Kern [4] measured an emissivity of 0.916 for dry quartz sand and 0.936, when the sand was nearly saturated with water. Falckenberg [2] and Fuchs & Tanner [3] reported emissivity values of dry sand close to 0.90. It was also found [3] that high water-contents raise the emissivity significantly. An increased emissivity (0.96) was measured for clayey and loamy soils by Hovis [1]. He also found that changes in moisture content of these soils hardly affect their emissivities.

In this paper, results are reported from ground-based emissivity measurements on three different soils in the 9.5-11.5 μm wavelength interval. Main-objectives of the experiment were to further study the emissivity dependence on soil-type, porosity, soil-moisture and surface roughness. Results from simultaneous measurements of the soil-reflectance in the 0.50-0.62 μm wavelength interval are also presented and compared.

2. METHODOLOGY

2.1 Equipments

During August 1983, ground-based emissivity measurements were carried out on different soil-types using a Barnes PRT-5 IR-radiometer, which was connected to a chart recorder. The instrument senses the thermal radiation in the wavelength interval 9.5-11.5 μm and has a field of view of two degrees.

Besides the emissivity, the reflectivity of the soil-samples between 0.5 and 0.6 μm was also estimated, using a Hagner S2-photometer and Kodak plates as a reference.

Soil types used at the experiments were quartz sand, clay and humus-soil.

At the measurements, the soil-samples were placed on the bottom of a shallow box (0.90x0.7x0.2 m). The top of the box was covered by two flaps, which could be turned aside, exposing the soil-samples to the cold sky. The IR-radiometer was placed on a tripod beside the box and with the sensitivity beam pointing down to the soil-samples at a zenith-angle of 20 degrees. When the box was closed, the radiometer looked at the soil-samples in the box through a rectangular hole (0.14x0.20 m). The emissivities of the test-soils were estimated from measured IR-temperatures before and after the box opening.

2.2 Analysis

When the box is open, the detected IR-radiation from the soil-sample can be described as

$$L_b(T_o) = \varepsilon_s L_b(T_{so}) + (1-\varepsilon_s)[p_o L_b(T_{eo}) + (1-p_o)\, L_b(T_{Bo})] \qquad (1)$$

where

T_{so} = soil-surface temperature

ε_s = emissivity of the soil

T_{eo} = radiation temperature of the incident external flux

T_{BO} = radiation temperature of the interior of the box

p_o = geometry factor defining the external portion of the radiation incident upon the soil surface and reflected towards the IR-sensor

The function $L_b(T)$ defines the spectral radiance of the black-body radiation averaged over the filter window of the sensor. Hence,

$$L_b(T) = \int_0^\infty h(\lambda)\, L_b(\lambda,T)\, d\lambda \qquad (2)$$

where $h(\lambda)$ is the spectral response of the IR-sensor normalized with respect to the maximum sensitivity ($h(\lambda) \leq 1$) and $L_b(\lambda,T)$ is the spectral black-body radiance. Similarly, the emissivities of Eq. (1) are to be interpreted as weighted averages over the wavelength window of the sensor.

When the box is closed, the detected radiation from the soil sample is described as

$$L_b(T_c) = \varepsilon_s\, L(T_{sc}) + (1-\varepsilon_s)[p_c\, L_b(T_{ec}) + (1-p_c)L_b(T_{Bc})] \qquad (3)$$

Almost all the reflected radiation comes now from the inside of the box (p_c <<1), and only sky radiation from a narrow sector around zenith is reflected by the soil-surface towards the IR-sensor.

Introductory measurements showed that the temperature of the walls of the box and the soil-samples changed slowly compared with the time required to open the flaps and get a recording. Hence, $T_{so} = T_{sc} = T_s$ and $T_{BO} = T_{Bc} = T_B$ during the seconds after a change of the box-state. The difference in detected radiation, when closing the box, is thus given by

$$\Delta L_b = L_b(T_c) - L_b(T_o) = (1-\varepsilon_s)[p_c L_b(T_{ec}) - p_o L_b(T_{eo}) + (p_o-p_c) L_b(T_B)] \qquad (4)$$

If p_o, p_c, T_{eo}, and T_{ec} are known, the emissivity ε_s can be computed from Eq. (4) and the measured IR-temperatures (T_o and T_c). The four parameters p_o, p_c, T_{eo}, T_{ec} can be estimated from the geometry of the box and the sensor arrangement, and by measuring the incident radiance from the sky hemisphere.

A more simplified approach is to use an object with well-defined emissivity as a reference. If measurements on a test object and the reference are carried out consecutively, the four parameters p_o, p_c, T_{eo}, T_{ec} will not change. From Eq. (4), the following emissivity estimate is then derived

$$\varepsilon_s = 1 - (1-\varepsilon_{ref}) \frac{L_b(T_c) - L_b(T_o)}{L_b(T_c^{ref}) - L_b(T_o^{ref})} \qquad (5)$$

Several calibration references were used at the experiment. A primary one was produced from an aluminium foil, which was crumpled up, unfolded and slightly stretched in order to achieve diffuse reflectance performance. Comparative measurements of the direct and reflected zenith-radiation showed that the emissivity of the smooth foil was very close to zero.

Calibration measurements on a concrete slab gave T_c = 286.2 K and T_o = 284.8 K, compared to T_c = 278.0 K and T_o = 251.3 K for the rough aluminium foil. Insertion into (5) with $\varepsilon_{ref} = 0$ yields $\varepsilon_{concrete} = 0.93(4)$ Similarly, the emissivity of dry porous sand with a smooth surface was estimated to 0.90(3).

The concrete plate and the smooth dry sand were also used as secondary references. In this case, the measured IR-temperatures of the reference and the test objects are closer, which makes a linearization of $L_b(T)$ relevant. Hence,

$$\varepsilon_s \approx 1 - (1-\varepsilon_{ref}) \frac{(T_c - T_o)}{(T_c^{ref} - T_o^{ref})} \qquad (6)$$

The random error of the output signal was reduced by repeating the same measurement three or four times. A preliminary analysis of the accuracy of the estimated emissivities indicated errors on the order of 0.003. Repetitions of similar measurements showed that this accuracy can be achieved at relative measurements in the same series, while higher errors sometimes occurred when measurements from different days were compared.

3. EXPERIMENTAL RESULTS

3.1 Soil-types

Repeated measurements showed that the emissivity of dry quartz sand was close to 0.90, while ε = 0.95-0.96 was typical to the fine-grain soils; the results agree well with earlier measurements by Hovis [1], Falckenberg [2], and Fuchs & Tanner [3].

3.2 Surface roughness

Surface roughness effects were studied by comparing the emissivities of humus and clay soils, which had been prepared in two different ways (Table 1). One set had smooth surfaces, achieved by first moistening the soils followed by drying. The other samples had a rougher surface with a large number of small clods. As shown by Table 1, the rough surfaces showed about one per cent higher emissivity values than the smooth ones.

Another experiment was performed on a porous sand surface, which was made smooth by light taps. Then the surface was scratched with a pencil following a square pattern of size 10x10 mm. As shown by Table, the emissivity of the roughened sand surface increased one to two per cents compared to the smooth one. The change increased with the depth of the furrows. The enhanced emissivity of a rough surface is expected, since it is well-known that surface roughness reduce the reflectance due to an increased probability of multiple-reflections. According to Kirchoff ($\varepsilon = 1-R$), this is equivalent to an increased emissivity.

3.3 Porosity

The effects of varying porosity were studied using soil-samples of dry clay and humus soils, which were finely broken up in porous layers. The soil-surfaces were also smoothed before the emissivity measurements using a soft brush. The high-porous soil-layers were then compressed with a pressure on the order of 100 000 Pascals, after which the measurements were repeated.

As shown by Table 2, the emissivity decreased about 0.5-1.0 % when the porosity changed from high to low values. A significant increase of the reflectivity at 0.55 µm was also observed. (Table 2.)

An increased emissivity of porous soils should be expected from theoretical points of view, because high-porous soils should have a rougher surface at small-scale level. For fine-grain soils, a reduced index of refraction is also obtained, which means lower Fresnel reflection coefficients and according to Kirchoff an increased emissivity.

3.4 Soil-moisture

Repeated emissivity measurements were carried out on sand, clay and humus soils of varying soil-moisture. In order to study the wavelength influence, comparative reflectance measurements were also performed in the interval 0.50-0.62 µm. At the start of the experiment, about 5 mm thick soil-layers were formed and saturated by water, after which the excess water was removed by tilting the soil-samples a few minutes. Emissivity, reflectance and water losses were then measured repeatedly during the outdoor drying phase, which mainly took place in shadow. The estimated soil-moisture represents the average water content by weight of the soil-layers. This is only an approximative measure of the surface wetness, which primarily affects the emissivity.

The results of the experiment show that the emissivity of sand is changed from about 0.90 (dry sand) to 0.94-0.96 at high water contents (Figure 1). The emissivity of clay and humus soils decreased only one or two per cent when the soil-samples dried up. It was also observed that the emissivity of sand was close to the dry value when the soil-moisture content was lower than ten per cent, while fine-grain soils approached the dry limit at higher water contents.

The soil-moisture dependence of the reflectance in 0.50-0.62 μm shows quite different characteristics compared to the thermal-IR band. All soil-types looked wet and dark as long as the soil-moisture exceeded 15 %. They all showed high reflectance differences between dry and wet states. Typically, the reflectance of dry soils exceeds the wet reflectance values by a two-factor.

Increased emissivities of wet soils are expected, since the emissivity of water is higher than for mineral objects. In order to change the reflectance/emissivity significantly the thickness of the water film around the particles should exceed 10 per cent of the wavelength. This explains why e.g. a wet sand surface at low water contents looks dry at thermal-IR but wet in the visible band (Fig. 1). For soils with particle sizes much smaller than the wavelength, the waves interpret the soil-water mixture as homogeneous with an index of refraction defined by the refractive indices of the constituents and affected by their relative proportions. From Fresnel's reflection coefficients, it is then found that the soil-moisture influence is highly reduced.

4. CONCLUSIONS

The experiment confirms that the emissivity of dry quartz sand is close to 0.90 while 0.94-0.96 is typical for fine-grain dry soils with smooth surfaces.

Furthermore, it was shown that the emissivity increases one or two per cent for high-porous soils or when the surface is rough. A similar increase is obtained for fine-grain soils with high water contents, while up to six per cent increase was observed for very wet sand.

Comparisons with reflectance measurements in the visible band (0.50-0.62 μm) show that soil-moisture highly affects the soil reflectance independent of soil-type. Compared to the thermal-IR wavelength interval, the short-wave reflectance is changed at much lower water contents and with large differences in reflectance between dry and wet soils. The trends of the results can be explained in qualitative terms from Fresnel's and Kirchoff's reflectance and emissivity coefficients and the refractive indices of the soil constituents. A more detailed analysis should include radiative transfer and multiple scattering theory.

ACKNOWLEDGEMENTS

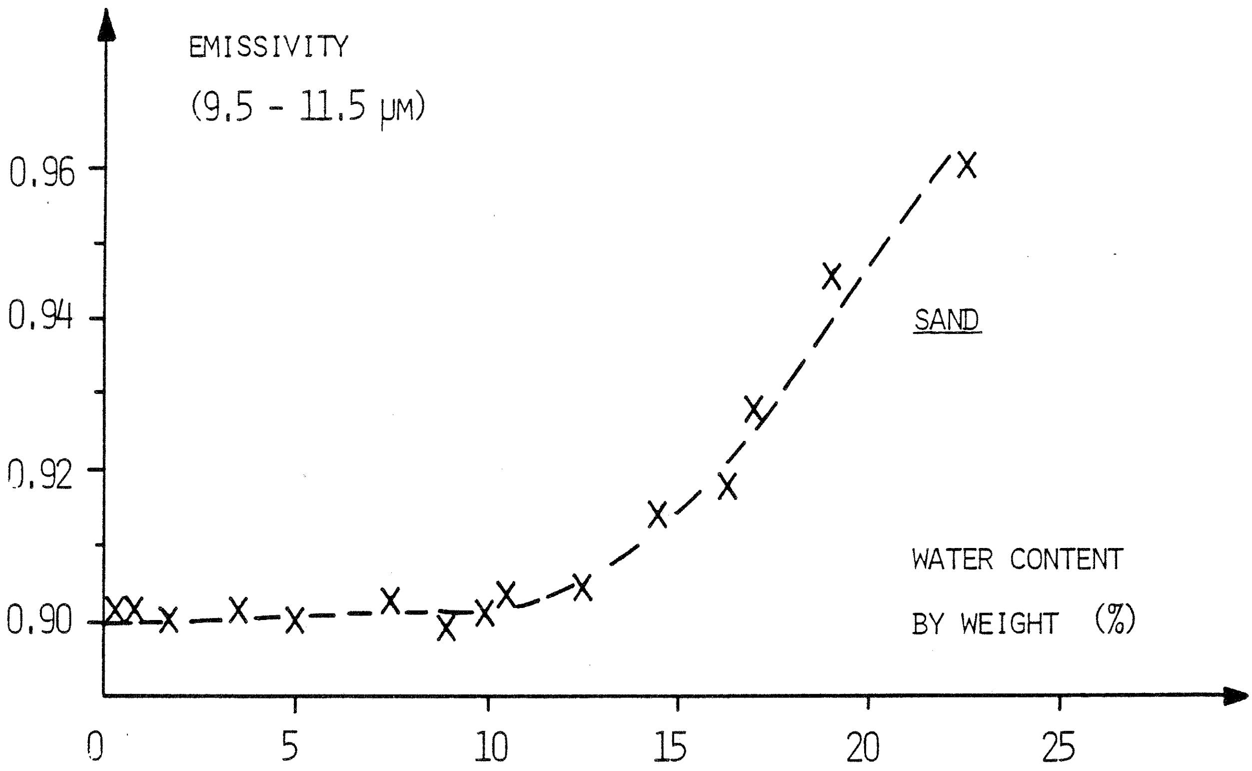
This work was supported by the Swedish Board for Space Activities. Equipments necessary for the measurements were provided by the Swedish National Road Administration and SAAB-SCANIA AB.

TABLE 1: Measured emissivity (9.5-11.5 μm) of soil-samples with varying surface roughness.

SOIL TYPE	EMISSIVITY
1. Dry crumbly humus-soil	0.96 (2)
2. Dry humus-soil with smooth surface	0.95 (3)
3. Dry crumbly clay	0.96 (3)
4. Dry clay with smooth surface	0.94 (5)
5. Dry sand with smooth surface	0.90 (0)
6. Dry sand with shallow furrows	0.91 (3)
7. Dry sand with deeper furrows	0.92 (0)

TABLE 2: Measured emissivity (9.5-11.5 μm) and reflectivity (0.55 μm) of fine-grain soil-samples with smooth surfaces but varying porosity

SOIL TYPE	EMISSIVITY	REFLECTIVITY
1. Dry porous humus-soil	0.95 (6)	0.12
2. Dry dense humus-soil	0.94 (9)	0.15
3. Dry porous clay	0.96 (0)	0.19
4. Dry dense clay	0.95 (3)	0.24



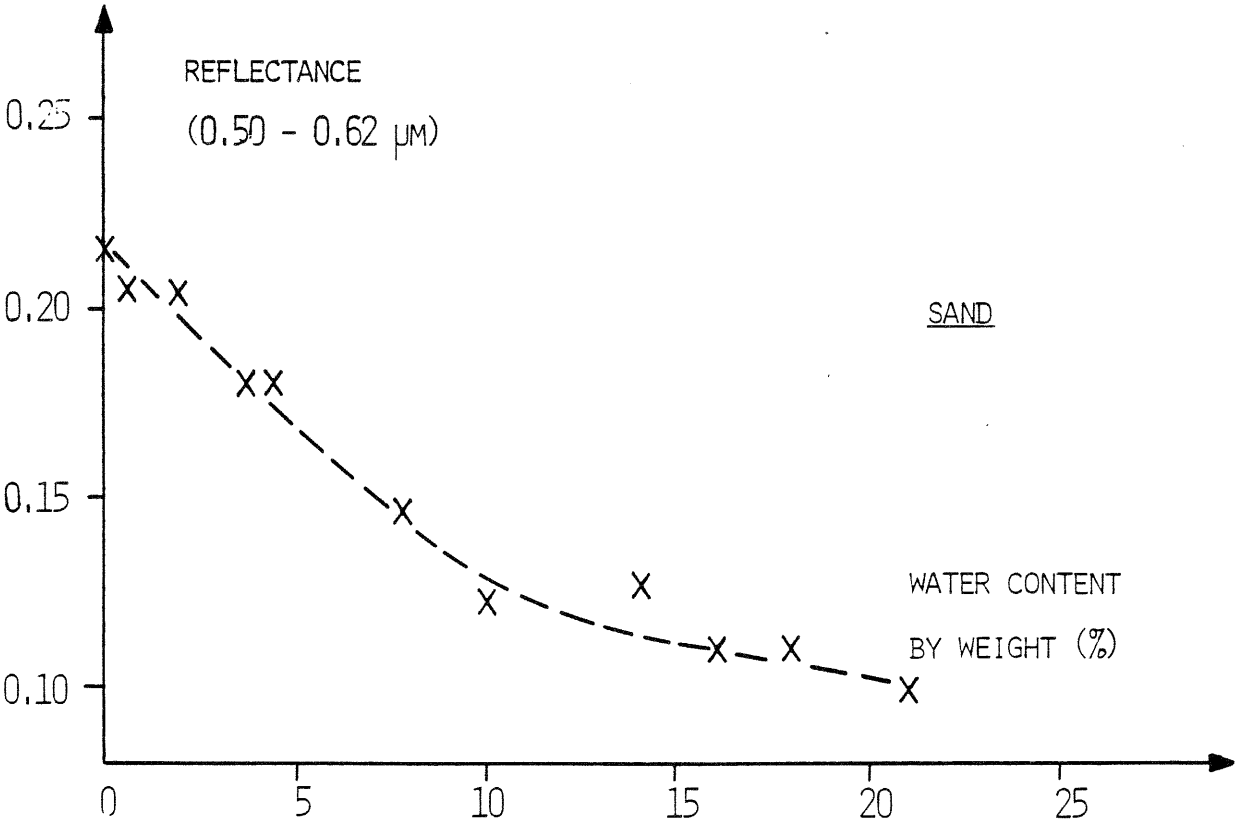
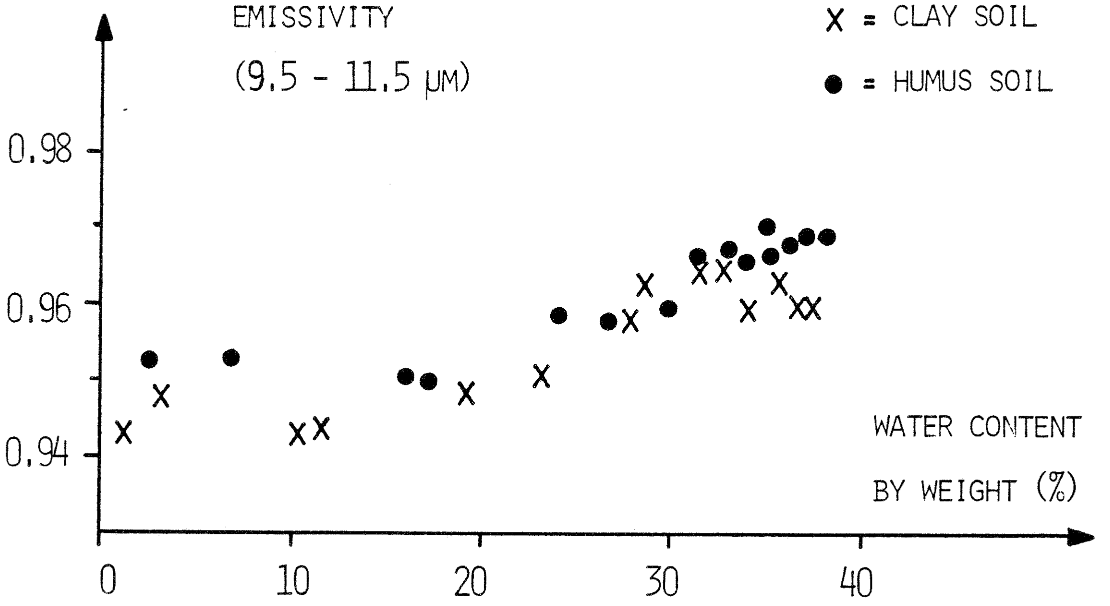


FIGURE 1: Measured emissivity and reflectance of sand versus soil moisture.



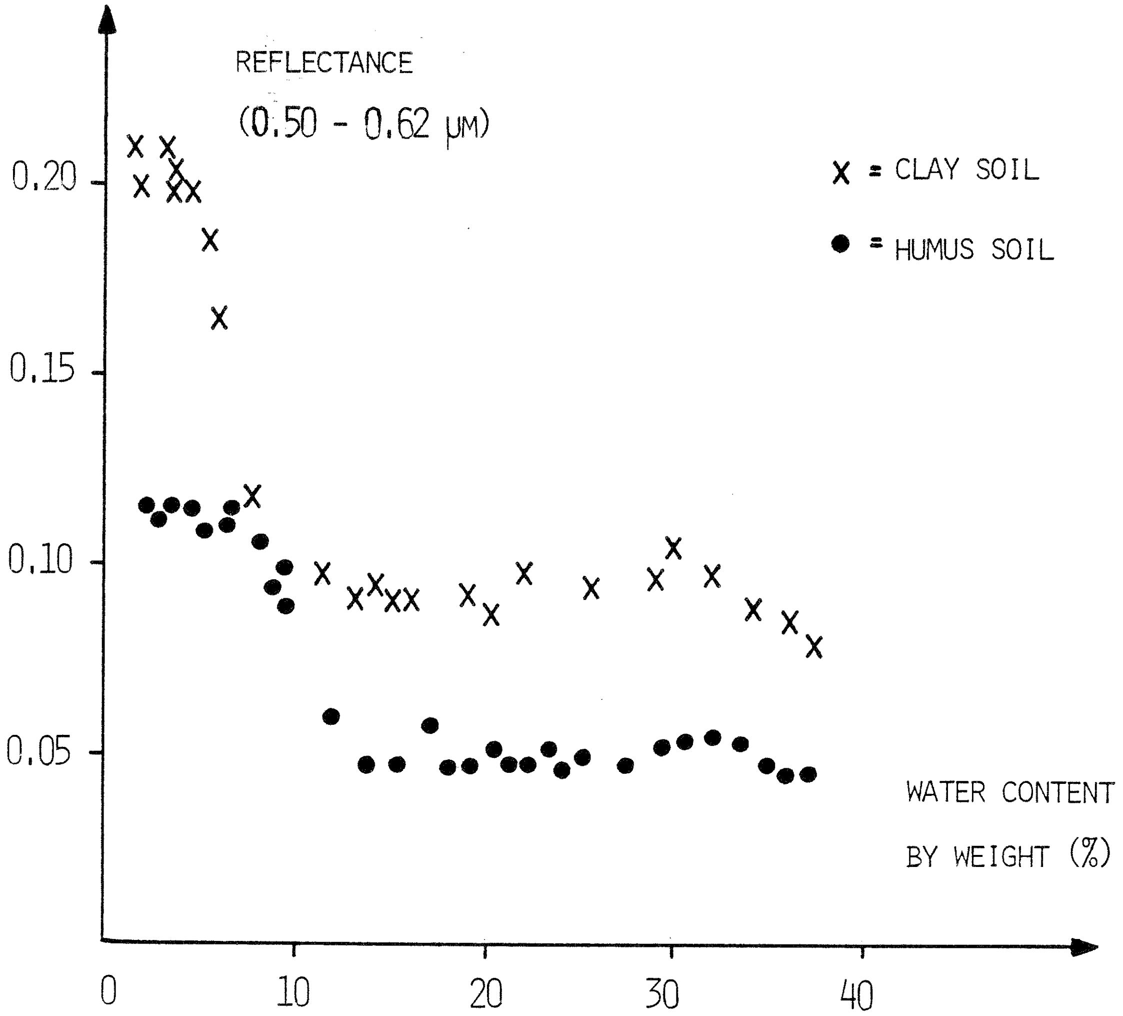


FIGURE 2: Measured emissivity and reflectance of clay and humus soils versus soil-moisture.

REFERENCES

[1] Hovis, W.A., "Optimum wavelength intervals for surface temperature radiometry." Appl. Opt. 5 (1966): 815-818.

[2] Falckenberg, G., "Die Absorptionskonstanten einiger meteorologisch wichtiger Körper für infrarote Wellen." Meteor. Z. 45 (1928): 334-337.

[3] Fuchs, M., and Tanner, C.B., "Surface temperature measurements on bare soils." J. Appl. Meteorol. 7 (1968): 303-305.

[4] Buettner, K.J.K, and Kern, C.D., "The determination of infrared emissivities of terrestrial surfaces." J. Geophys. Res. 70 (1965): 1329-1337.

[5] Vlcek J., "A field method for determination of emissivity with imaging radiometers." Phot. Eng. Rem. Sens. 48 (1982): 609-614.