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Thermal Properties and Shrinkage-Swelling Characteristic of Clay Soil in a Tropical Paddy Field

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Abstract

Thermal conductivity (K) as functions of water content (w) is not so well known for swelling soils as that for non-swelling soils. We measured K and thermal diffusivity of a swelling soil taken from paddy fields in Indonesia, together with its shrinkage-swelling characteristic. The soil showed remarkable shrinkage-swelling nature ; void ratio of the soil in-situ exceeded 2.0 when flooded condition whereas it became less then 1.0 when the soil was dry. Observed K increased from 0.60 to 1.28 $\mathrm{W\,m^{-1}\,K^{-1}}$ with w increased from zero to 0.24 $\mathrm{g\,g^{-1}}$. However, for w greater than 0.24 $\mathrm{g\,g^{-1}}$, K decreased gradually with increase in w, differently from non-swelling soil that shows monotonic K increase with w. The decrease in K with increase in w must be produced by increased void ratio. As a result, the value of K for the soil of most dry condition in the field (K=0.99 $\mathrm{W\,m^{-1}\,K^{-1}}$) was almost the same as the value of K for flooded condition. Consequently, drying of the swelling soil has no effects of reducing heat conduction from surface into the soil when it is exposed to sunshine.

Key words : thermal conductivity, thermal diffusivity, swelling soil, paddy field, shrinkage-swelling characteristic

1. Introduction

Thermal properties of soil are necessary to predict heat flow and temperature changes in soil. The heat flow in soil is proportional to the temperature gradient in soil, and the proportionality coefficient is thermal conductivity. Another soil thermal property, thermal diffusivity, is defined as the ratio of thermal conductivity to volumetric heat capacity, and is a measure of the rate of transmission of temperature change into soil, when the surface temperature changes with time. Soil thermal conductivity and diffusivity depend on soil composition, bulk density, particle shape, and especially water content. A number of measurements have been conducted for thermal conductivity of non-swelling soils. General tendency of them as functions of water content is well known ; the thermal conductivity of non-swelling soil monotonically increases with increase in water content (θ). Thermal conductivity of water is about twenty times greater than that of air ; if soil air is replaced by water in the process of increasing soil water content, thermal conductivity must increase with water content (de Vries D.A., 1963). On the other hand, increase in bulk density (by compaction) increases thermal conductivity. Empirical equations for these relations have been also proposed (Campbell, 1985).

In paddy fields, there often exists surface soil containing swelling clay minerals. Because of puddling practice of every time of paddy culture, its original soil structure has been lost and single-grained structure is formed. These soils in paddy field remarkably swell by wetting and shrink by drying. The relation of thermal conductivity with water content of the swelling soil is significantly different from that of non-swelling soil because water content change of the swelling soil is accompanied by the change in bulk density. However, thermal conductivity of the swelling soil with relation to water content or bulk density is not well-known.

We measured thermal conductivity of a swelling soil in paddy field in Indonesia in the laboratory. The paddy field becomes uncultivated and dry bare soil with cracks is exposed during dry season of the tropical climate. Therefore, in order to estimate evaporation from the paddy field, thermal properties of the paddy field soil, as functions of water content or bulk density, are necessary to calculate the heat flow into or out of the soil that is a component of heat exchange at the soil surface.

2. Material and Methods

2.1 Location of soil sample

Soil sample was taken from a paddy field in Cidanau watershed, located northwest of Java island, Indonesia (between 105°52′E–106°03′E and 6°8′S–6°17′S). This area is part of the tropical monsoon region, in which the rainy season and the dry season are explicitly distinguishable. This watershed receives a great deal of precipitation : average annual rainfall is about 2,500 mm. Since average daily temperature is high and constant all year around (26–27℃), rice can be cultivated in the paddy fields at any time of the year as long as water is available ; up to three times cultivation of rice in a paddy field in a year is feasible if water is available in the paddy field during dry season. The ratio of cultivated area of the paddy fields to the total area of the paddy fields during dry season and wet season are 54% and 80%, respectively (Yoshikawa and Shiozawa, 2006). The uncultivated paddy fields expose dry bare soil with cracks during dry season.

The soil has 62.9% clay, 29.72% silt, and 5.9% sand content (Yoshino and Ishioka, 2005). Remarkable swelling-shrinkage and cracking phenomena observed in the paddy fields are responsible for the swelling property of the clay.

To obtain field water content, we selected two paddy fields and sampled soils of both fields. One soil sample was taken from a paddy field in flooded condition (wet field), and the other sample was taken from uncultivated paddy field in dry condition (dry field). The water contents of the sampled soils were determined by oven drying (105℃) and weighting in laboratory.

2.2 Shrinkage-swelling characteristic

Shrinkage-swelling characteristic is expressed by void ratio (e) as a function of moisture ratio (ϑ). ϑ and e are defined as follows,

$$\vartheta=\frac{V_w}{V_s} \tag{1}$$

$$e=\frac{V_f}{V_s} \tag{2}$$

where V_s is volume of solid, V_w is volume of water, and V_f is volume of void (fluid ; air and water). Volumetric water content (θ) is given from ϑ and e by

$$\theta=\frac{V_w}{V_s+V_f}=\frac{\vartheta}{(1+e)} \tag{3}$$

For saturated condition, $V_\mathrm{w}=V_\mathrm{f}$, and $\vartheta=e$. Therefore, θ of saturated condition (θ_s) is given by

$$\theta_s=\frac{e}{1+e} \tag{4}$$

Shrinkage-swelling characteristic was determined by measuring volume and mass of the soil (including water inside soil) and soil volume on changing water content. Initially soil paste with 0.67 g g^{-1} water content ($\vartheta=1.7$ cm^3 cm^{-3}) was made and put in a container to have a size of 6.5 cm wide, 11 cm long, and 3.5 cm deep. The soil paste was dried slowly by evaporating water in a room (the room temperature was 17–20℃, but not controlled) to prevent unequal vertical deformation due to quick evaporation. Several times during evaporation, volume of shrunken soil and mass of lost water were determined by measuring length of three size of the soil block, and weighing. Bulk density was calculated using the soil volume mass of water and mass of dry soil that was obtained by oven-drying after the evaporation experiment.

2.3 Crack area measurement

Due to strong shrinkage-swelling nature of the soil, large cracks are formed in uncultivated dry paddy field. To measure cracks area, image of dry paddy field with crack taken by a digital camera was analyzed. Image analysis with thresholding methods of pixels (using ImageJ) separated object into soil surfaces and the cracks only.

2.4 Soil thermal conductivity measurement

Thermal conductivity of the soil was measured by probe method described by Shiozawa and Campbell (1990). Thermal conductivity probe (Decagon Devices Inc., USA) is 60 mm length-1 mm diameter stainless steel pipe in which a resistive heating wire and a copper-constantan thermocouple is inside.

Soil of higher water content was prepared from mixing initially dry soil (oven-dried) and water to make clay paste with certain water content. The clay paste was then put into container size of 12.5 cm long, 5.5 cm wide, and 5 cm height. The thermal conductivity probe was inserted to the soil. During wet condition, the thermal conductivity probe can be inserted easily into the soil. Soil block of lower water content than 0.6 g g^{-1} was prepared by gradually and slowly dried the soil in the container, keeping it in a room temperature in the same way as the shrinkage experiment. As the soil drying, the heat probe was keep inside the soil.

Heat was generated in the probe for a short time by a constant current through a heating wire and thermal conductivity was determined by measuring the probe temperature change during the heating period and/or subsequent cooling period. For the heating period, temperature of the probe, T, is given by

$$T-T_o=(q/4\pi K)\ln(t+t_o)+d \text{ for } t<t_1 \quad (5)$$

where K is thermal conductivity of the soil [W m^{-1} K^{-1}], q is heat generated per unit length of the probe, T_o is initial probe temperature [℃], t_1 the heating time [second], t_0 and d is empirical constants. Temperature in the soil will fall if the heating current is switched off. During this period, an imaginary heat sink removes the same heat which exists previously. The temperature in the cooling period is the result of superposition of effects of the imaginary heat source and sink. Therefore probe temperature during the cooling period is given by

$$T-T_o=(q/4\pi K)\ln(t+t'_o)-\ln(t-t_1+t'_o)+d' \text{ for } t>t_1 \quad (6)$$

where the parameters t_o' and d' may be different from t_o and d in the equation 5.

A data logger/controller CR21X (Campbell Scientific Inc. Logan, USA) was used for the thermal conductivity probe measurement. CR 21X controls switching of the heater and measures temperature of the probe. Heating period was 120 seconds with the voltage of heating in the probe up to 600 mV (q is 4.5 W m^{-1}).

K, t_o, d in equations (5) and (6) were determined separately for heating and cooling periods by using least squares optimization procedure. The data in the first five seconds of heating and cooling are excluded from the analysis to eliminate the bias caused by effects of probe thermal properties. Examples of the measured and fitted heating and cooling T-t curves are shown in Fig. 1. The observed values fit theoretical curves quite well. Resulting thermal conductivity is acquired by averaging K values from heating and cooling periods.

Thermal diffusivity (D) is defined as the ratio of thermal conductivity (K) to heat capacity of the soil (C_h) :

$$D=\frac{K}{C_h} \quad (7)$$

The volumetric heat capacity of a soil can be calculated as the sum of the heat capacities of the soil components. Soil is made up of minerals, water, and organic matter. The soil heat capacity is therefore computed from (Campbell, 1985) :

$$C_h=C_m\phi_m+C_w\theta+C_a\phi_a+C_o\phi_o \quad (8)$$

where ϕ is the volume fraction of the component [m^3 m^{-3}] indicated by the subscript. Subscripts, m, w, a, and o indicate mineral, water,

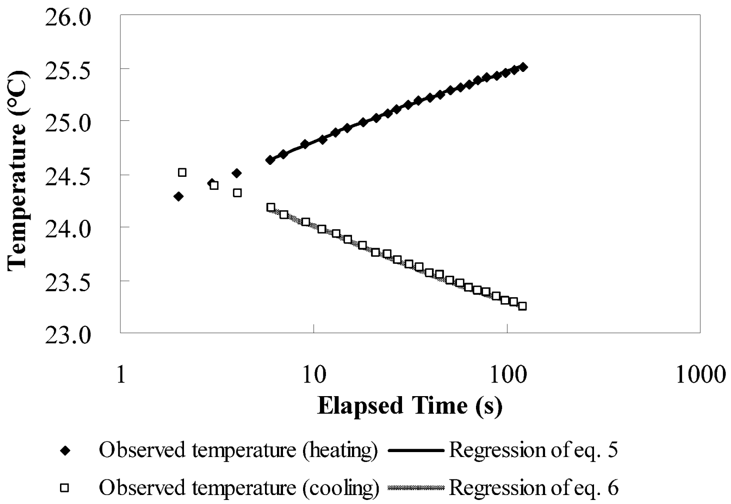

Fig. 1 Examples of temperature rise and down of a heat probe during heating and cooling period. Heating period was 120 seconds with heat of 4.5 $W\,m^{-1}$. Water content was 0.71 $g\,g^{-1}$.

air, and organic constituents. C is volumetric heat capacity [MJ $m^{-3}K^{-1}$]. Values of C for each of substances are 2.31 [MJ $m^{-3}K^{-1}$] for soil minerals, 4.18 [MJ $m^{-3}K^{-1}$] for water, and 2.5 [MJ $m^{-3}K^{-1}$] for organic matter. Volumetric heat capacity of air (C_a) is given as function of air temperature (Campbell and Norman, 2000).

In this experiment only two terms of the equation were used to calculate volumetric heat capacity, namely mineral and water substances. Neglected parts of equation 8 is because air considered to contributes only small amount to heat capacity, while organic matters found to be few (2%) in the soil. Thus, the heat capacity is given by

$$C_h = 2.31\phi_m + 4.18\theta \tag{9}$$

where C_h is expressed in MJ $m^{-3}K^{-1}$. For swelling soil, ϕ_m and θ are not easy to obtain due to the shrinkage-swelling characteristic, but can be calculated from ϑ and e. θ is given by equation (3), and ϕ_m is given by

$$\phi_m = \frac{1}{1+e} \tag{10}$$

3. Results and Discussion

3.1 Soil shrinkage-swelling characteristic

Figure 2 shows plot of void ratio (e) vs. moisture ratio (ϑ). General form of the swelling-shrinkage characteristic (SSC) curve contains normal shrinkage phase, residual shrinkage phase, and zero-shrinkage phase (Haines, 1923 in Bronswijk, 1988). On the other hand, Braudeau (1988) modeled ϑ-e curve based on the assumption that the soil consists of clayey microaggregates separated from each other and from the other soil constituents by a network of macropores. Braudeau (1988) divides swelling-shrinkage curve by four point ; shrinkage limit (SL), “air entry” in the microaggregates (AE), the limit of contribution of macroporosity to shrinkage (LM), and the maximum swelling of the microaggregates (MS) (Garnier *et al.*, 1997). However, it is apparent that the observed ϑ-e curve shows the typical three phases of normal, residual and zero shrinkage. Since the soil was made into puddle with water as it was in the field, it had no microaggregates or structure.

Field observation in dry season indicated that surface soil of a sufficiently wet paddy field (irrigated and slightly ponded) had water

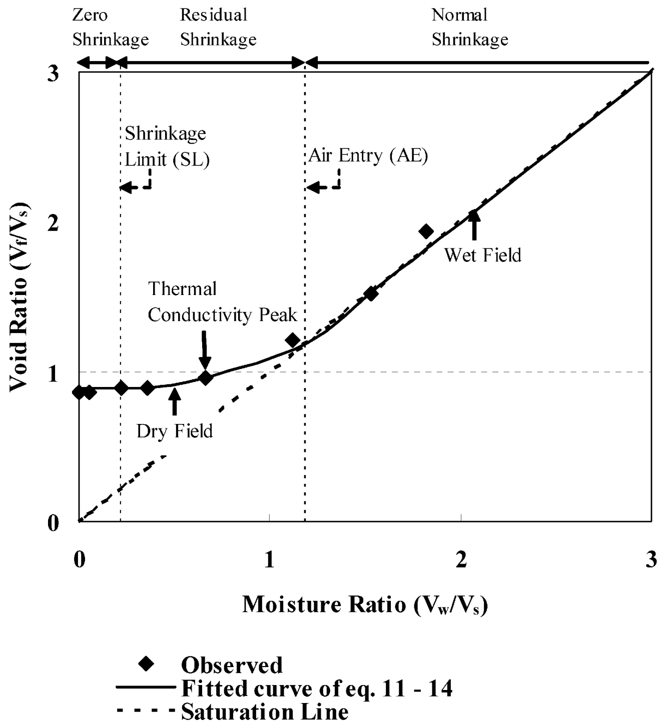

Fig. 2 Shrinkage-swelling characteristic of the soil with three phases. Solid arrows indicate moisture ratios observed in fields of wet and dry conditions, and that gives the thermal conductivity peak in Fig. 5. Dashed lines and arrows indicate shrinkage limit and air entry.

content of 0.95 g g^{-1} and that of a dry paddy field (uncultivated) had water content of 0.16 g g^{-1}. Mapping these values of moisture ratio and void ratio in the ϑ-e curve (Fig. 2) indicates that soil of dry paddy field lies in the residual shrinkage zone, while soil of wet paddy field lies in the normal shrinkage zone where water content is saturated.

SSC curve for the curve range 0-SL, SL-AE, and after AE is expressed by the following equations :

a. Zero-shrinkage

$$e = e_{SL} \tag{11}$$

b. Residual shrinkage

$$\mathrm{e} = \mathrm{e}_{\mathrm{SL}} + \mathrm{K}_{\mathrm{r}}\left[\frac{\vartheta_{\mathrm{AE}} - \vartheta_{\mathrm{SL}}}{\exp(1) - 1}\left(\exp(\mathrm{V}_{\mathrm{n}}) - 1 - \mathrm{V}_{\mathrm{n}}\right)\right] \tag{12}$$

$$\mathrm{V}_{\mathrm{n}} = \frac{\vartheta - \vartheta_{\mathrm{SL}}}{\vartheta_{\mathrm{AE}} - \vartheta_{\mathrm{SL}}} \tag{13}$$

c. Normal shrinkage

$$\mathrm{e} = \mathrm{K}_{\mathrm{r}}(\vartheta - \vartheta_{\mathrm{AE}}) + \mathrm{e}_{\mathrm{AE}} \tag{14}$$

Values of parameters in equations obtained by fitting them to observed data are : $\vartheta_{SL} = 0.22$ [$cm^3\,cm^{-3}$], $e_{SL} = 0.88$ [$cm^3\,cm^{-3}$], $\vartheta_{AE} = 1.19$ [$cm^3\,cm^{-3}$], $e_{AE} = 1.19$ [$cm^3\,cm^{-3}$], and $K_r = 1$. Subscript SL indicates "Shrinkage Limits", and subscript AE indicates "Air Entry".

The coefficient K_r which equal to 1 shows that during normal shrinkage the volume change is equal to moisture change. In addition $e = \vartheta$ of equation (14) means that soil is saturated. This gives straight line of 45-degree slope that passes (0, 0) in Fig. 2. Three observed points that lie on the straight line indicate that this soil has the volume change of normal shrinkage for $\vartheta > 1.2\ cm^3\,cm^{-3}$. Residual shrinkage is the process of reducing water content follows entering of air into soil and shrinkage simul-

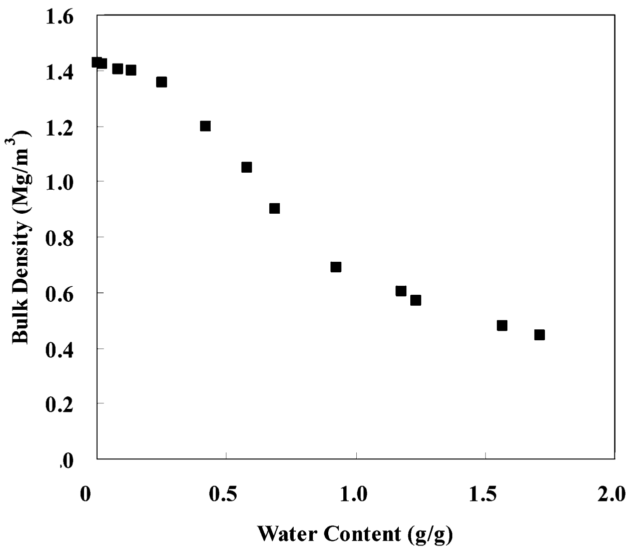

Fig. 3 Relationship between bulk density and water content of the swelling soil.

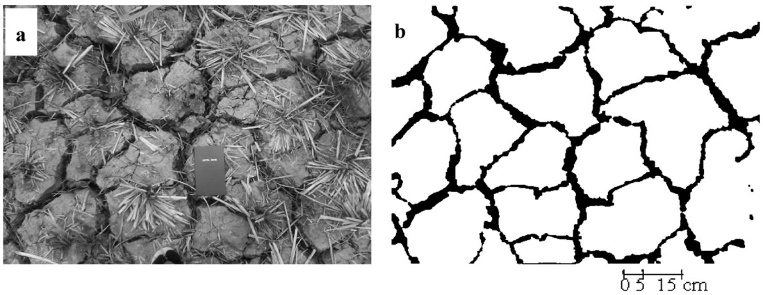

Fig. 4 Crack pattern in paddy field. (a.) Dry paddy field with crop plant residue and cracks. (b.) Image of a. which thresholded for soil surface and cracks only. Crack opening is 16% of surface area.

taneously. In zero shrinkage, reducing water content occurs without shrinkage.

The relationship of bulk density and mass base water content is shown in Fig. 3. In rigid soil, the values of bulk density vary with structural condition of the soil, particularly related to packing. Unlike rigid soil, bulk density of the swelling soil is variable with water content. The bulk densities vary from 1.4 Mg m^{-3} to 0.4 Mg m^{-3} with increasing water content up to 1.7 g g^{-1}.

Figure 4 shows observed crack pattern for 1.05 m^2 of paddy field surface. As a result, area of soil surface in the image was 0.88 m^2 (84%) and that of crack opening was 0.17 m^2 (16%). Neglecting cracks in the edges of the image, the average surface area of one block surrounded by cracks is 676 cm^2.

3.2 Thermal conductivity

Figure 5 shows the relation of thermal conductivity (K) to mass base water content (w). For water contents lower than 0.24, K increases steeply with increase in w. By contrast, for water contents larger than 0.24, K decreases with increase in w due to increase in bulk density. This relation is different from K-w relation of non-swelling soils, which generally shows monotonic K increase with the increase in

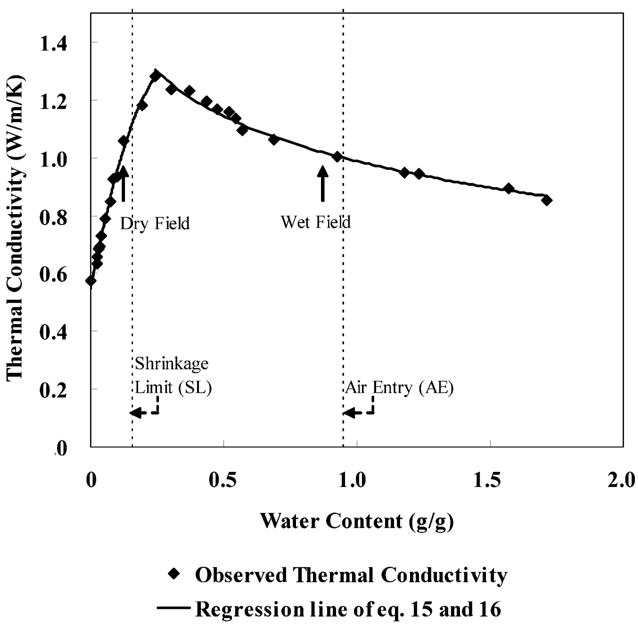

Fig. 5 Relationship between thermal conductivity and water content of the swelling soil. Solid arrows indicate water contents observed in fields of wet and dry conditions.

water content at an ordinary temperature (e.g. Campbell, 1985 ; Hiraiwa and Kasubuchi, 2000). The thermal conductivity value corresponds to w of the wet (cultivated and flooded) paddy field during field observation ($w=0.95\,\mathrm{g\,g^{-1}}$) was $1.16\,\mathrm{W\,m^{-1}\,K^{-1}}$, while that correspond to w of dry paddy field ($w=0.16\,\mathrm{g\,g^{-1}}$) was $0.99\,\mathrm{W\,m^{-1}\,K^{-1}}$. K value of the flooded paddy field soil was similar to that observed in a flooded paddy field in Japan by Mowjood *et al.* (1997), which was $0.90\,\mathrm{W\,m^{-1}\,K^{-1}}$. It is surprising that the thermal conductivity value for very dry soil and that for sufficiently wet soil are almost the same ; generally for non-swelling soil, K of water saturated condition is several times as much as K of most dry condition. The maximum value of thermal conductivity is $1.28\,\mathrm{W\,m^{-1}\,K^{-1}}$ at water content value of $0.24\,\mathrm{g\,g^{-1}}$. This water content exists in the middle position between zero shrinkage and normal shrinkage in Fig. 5.

These phenomena can be explained by comparing three values of thermal conductivity of soil constituents. Thermal conductivity of air, water and soil mineral are 0.024, 0.56, and 2.5 [$\mathrm{W\,m^{-1}\,K^{-1}}$] (de Vries 1963 ; Campbell and Norman, 2000). Roughly the ratio of air : water : soil particle is 1 : 20 : 100. If void ratio is constant with changing water content (for non-swelling soil or zero shrinkage zone of swelling soil), increasing water content occurs by replacing air (lowest K) in pores by water (the second highest K) of the same volume and it results in increasing thermal conductivity. This effect of increasing K with increasing w is significant when air exists at contact point of solid particles (highest K) is replaced by water. For non-swelling soils, of which void ratio is constant, K must increase monotonically with increase in w. However, for water saturated or nearly water saturated condition of the swelling soil, increasing water content occurs by increasing void ratio, that is decreasing solid volume of the same (or similar) amount of the increased water ; therefore, it must result in decrease in K.

Regression equation that expresses thermal conductivity as function of w is :

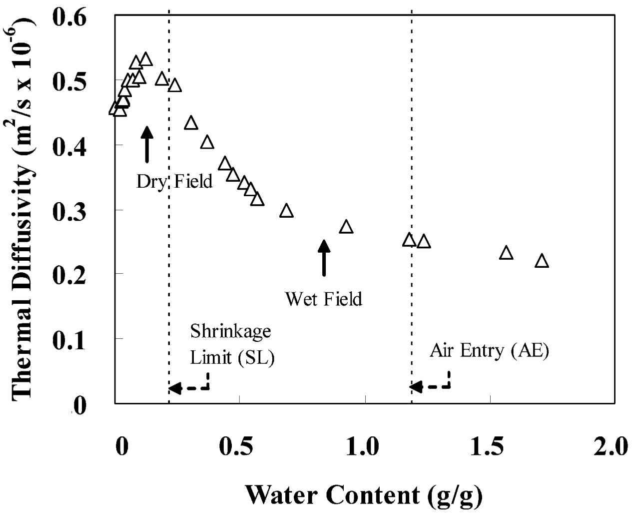

Fig. 6 Relationship between thermal diffusivity and water content of the swelling soil. Solid arrows indicate water contents observed in the paddy fields of wet and dry conditions.

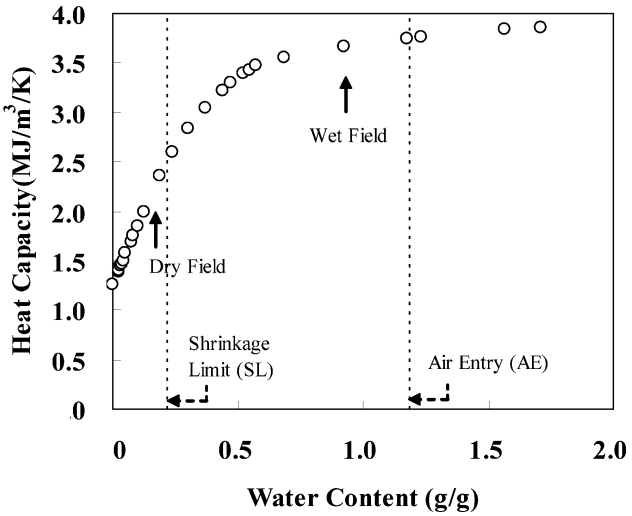

Fig. 7 Relationship between volumetric heat capacity and water content of the swelling soil. Solid arrows indicate water contents observed in the paddy fields of wet and dry conditions.

for $0 < w < 0.24$

$$K = -7.47w^2 + 4.83w + 0.55 \quad (15)$$

for $0.24 < w$

$$K = -0.224\ln(w) + 0.99 \quad (16)$$

Figure 6 shows the diffusivity of the soil that is calculated by equation (7) and (9). The diffusivity (D) basically decreases with increase in w except for very dry condition in which diffusivity slightly increase with w. Its peak value is observed at water content of $0.12\ \mathrm{g\,g^{-1}}$. The value of diffusivity ranges between 2.6×10^{-7} and $5.3\times10^{-7}\ \mathrm{m^2\,s^{-1}}$. At water content less than the peak value of thermal diffusivity, the rate of increase in thermal conductivity exceeds the

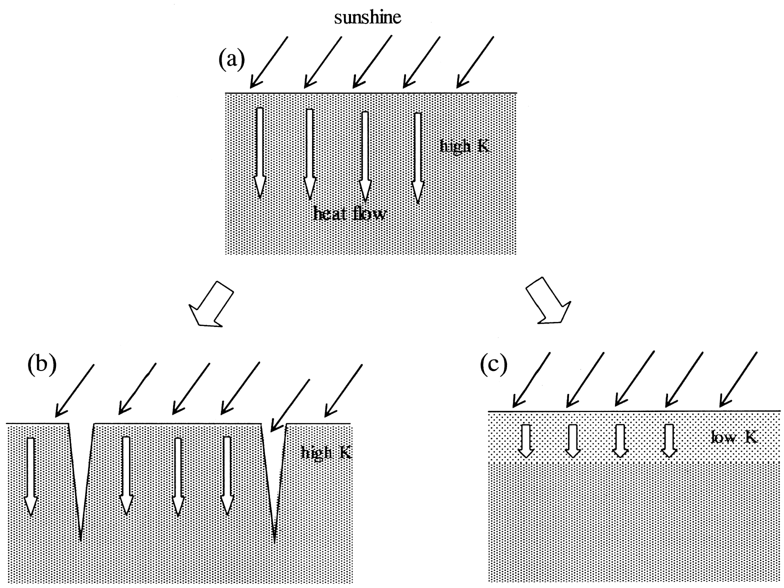

Fig. 8 Soil surface condition and heat flow in soil during daytime ; (a) wet condition of both swelling and non-swelling soil that have high thermal conductivity (K) ; K is high and heat flow is large. (b) dry surface of swelling soil with cracks ; K is high and heat flow is large even if cracks exist. (c) dry surface of non-swelling soil without cracks ; K is low and heat flow is small. Heat flows in the reverse direction during nighttime.

rate of increase in volumetric heat capacity (Fig. 7). At higher water content but less than that of the peak of K ($w=0.12-0.24\,\mathrm{g\,g^{-1}}$), the increase in heat capacity (C) exceeds increase in K and thus D starts decreasing. At water contents higher than that of the peak of K, decrease of K and increase of C resulted in steep decreasing of D with increase in w. However, for higher water content of $w>0.7$, K decrease slightly while C is nearly constant values, thus D decreases gradually with increase in w.

3.3 Effects of thermal conductivity of surface soil on heat balance

Thermal conductivity of the swelling soil as a function of water content is remarkably different from those of non-swelling soils. The values of K for the swelling soil of very dry soil and those of sufficiently wet (water saturated) soil are almost the same ; for non-swelling soil, K of nearly dry soil is much smaller than that of sufficiently wet soil. When the soils are dry, the values of K for the swelling soil are much larger than those of non-swelling soil because of high bulk density and probably good thermal contacts among clay particles for the shirked soil.

Thermal conductivity of the surface soil has important effects on heat balance at soil surface and formation of the surface temperature when the soil surface is exposed to sunshine. The higher soil thermal conductivity the more proportion of the heat from the sun flows into soil and stored in soil during day time ; surface temperature rise during daytime is thus restrained. On the contrary, when the surface soil has a low thermal conductivity, the low conductivity prevents heat conduction into soil and surface temperature rises more during daytime ; apparent heat flux from soil surface to air thus increases. In the uncultivated dry paddy field, surface temperature rise during the daytime would be less than that expected in upland dry fields, by a larger heat conduction into the soil due to higher thermal conductivity of the swelling clay soil.

3.4 Effect of cracks on heat flow in soil

Cracks are formed in the paddy field as soil dries. We consider that the cracks can be regarded as insulated spaces for heat conduction and also for heat convection because thermal conductivity of air is low and because convection of air should be limited in the narrow space of cracks (at most a couple of centimeters). However, the formation of the crack is vertical direction that is parallel to heat flow in soil (Fig. 8-b). It creates system of parallel heat resistance with crack resistance as one component. Resistance for heat flow parallel to heat flow has only minor effect on the heat flow, even if the resistance is extremely large. Opening area of cracks was about 16% of surface area and cracks closed at about 10 cm depth ; even assuming crack as insulator, the effect of cracks on thermal conduction is at most only 16% reduction within a few cm surface soil layer. Therefore, we think that heat flow in soil in the paddy field with cracks is approximately the same as the heat flow that would be observed in the soil of the same thermal properties but with no crack.

Existence of air in soil that is series to heat flow significantly resists heat flow in soil. This situation is expressed by the remarkably lower thermal conductivity of non-swelling soil of lower water saturation. In general, thermal conductivity of dry soil is about one order smaller in magnitude than that of water saturated soil. Due to such lower *K,* drying of the surface of non-swelling soil interrupt heat conduction (Fig. 8-c). On the other hand, drying of the swelling soil with forming of cracks does not reduce heat conduction significantly (Fig. 8-b).

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熱帯水田土壌の熱特性と収縮・膨潤特性

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要　　旨

代掻きされた粘土質水田の作土には著しい収縮・膨潤を示す土壌があるが，このような膨潤性土壌の熱伝導率（K）と水分量の関係はよく知られていない。そこで，インドネシアの水田作土土壌の，K，熱拡散係数，及び間隙比－体積含水比関係を測定した。この土壌は，著しい体積変化を示し，現場での間隙比は，湛水条件では 2 以上だが，乾燥状態では 1 以下であった。K は，含水比（w）が 0 から 0.24 g g^{-1} g^{-1} に増加する時，0.60 から 1.28 W M^{-1} K^{-1} に増加したが，w が 0.24 g^{-1} g^{-1} 以上では，w の上昇に伴い減少した。この w の増加に伴う K の減少は，膨潤土に特有で，間隙比の増加による。現場の乾燥時の K は 0.99 W M^{-1} K^{-1} で，湛水時の K とほぼ同じ値であった。このため，この水田土壌は非膨潤性土壌と異なり，表層が乾燥しても日射熱の土中伝導を妨げる効果がない。

キーワード : 熱伝導率，熱拡散係数，膨潤性土壌，水田，収縮-膨潤特性

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