EVALUATION OF THE STRUCTURAL DEVELOPMENT OF CLAYEY SOILS ON THE BASIS OF SHRINKAGE BEHAVIOR

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Received October 17, 1984

Introduction

The shrinkage behavior of clayey soils has been studied for remoulded soil blocks by TEMPANY (20), HARDY (5), HAINES (4), and SATO (15), for undisturbed soil clods by LAURITZEN and STEWART (9), LAURITZEN (8), STIRK (17), TAKENAKA (18), ARCA and WEED (1), GREEN-KELLY (3), REEVE and HALL (10), and REEVE, HALL and BULLOCK (11), and for undisturbed soil cores by BERNDT and COUGHLAN (2) and YULE and RITCHIE (23). As a results of these works, three shrinkage phases have generally been found when soils are dired from a very wet conditions; structural shrinkage (17); normal shrinkage (4, 20); residual shrinkage (4).

A number of works on the shrinkage of undisturbed soil clods or soil cores have been studied, directly or indirectly, in connection with soil structure. The idea that the structural development of a soil can be evaluated by comparing the dry specific volume of natural clods and of remoulded blocks of the same material was posturated by LAURITZEN (8). In the Stirk's work (17) and ARCA and WEED's work (1), total porosity was substituted for dry specific volume as the characteristic to be compared. On the other hand, the ratio of structural shrinkage to total shrinkage was used as an index of structural development by REEVE and HALL (10).

However, it is not considered that these proposals for the index of structural development have universally been accepted. We think this is due to the obscurity of physical meaning of proposed indexes.

The present study was undertaken to establish the index of structural development of field soils. It has four aims: (i) to compare the shrinkage behavior of undisturbed core samples from different clayey soils : (ii) to propose the index for the numerical evaluation of structural development ; (iii) to clarify the physical meaning of proposed index ; (iv) to clarify the relationship between proposed index and morphological soil structure in the soil profile.

Materials and Methods

1. Soil used

Thirty-five soils were sampled from nine soil profiles in central and southern Hokkaido. Location, soil classification and land use of these profiles are shown in Table 1.

Soil profiles of No. 1 to No. 4 are from volcanic ash soil and those of No. 26 to No. 126 are from nonvolcanic ash soil.

The fundamental properties of the soils are shown in Table 2.

These soils have clay contents ranging from 14.0 to 62.5%, organic matter contents from 0.7 to 27.9%, bulk densities from 0.53 to 1.49 g/cm^3, and void ratios from 0.81 to 3.56.

TABLE 1. Soil description

Profile No.	Location	Horizons	Genesis	Soil classification and Reference	Land use
1	Makkari-Mura	Ap/Al/B/C	Volcanic ash soil from Mt. Yōtei	Ordinary andosol, (12)	Grassland (Pasture)
2	Kuromatsunai-Cho	A/B/C	Volcanic ash soil from Taisei-tephra	Brown andosol, (14)	Grassland (Pasture)
3	Kitahiyama-Cho	A/C/IIA/IIC	Volcanic ash soil from Oshima-Ōshima, Mt. Komagatake, and so forth	Regosolic andosol, (13)	Grassland (Pasture)
4	Hakodate City	Ap/AC/IIAC/IIIAC/IVA/IVC	Volcanic ash soil from Mt. Esan, Mt. Komagatake, and so forth	Cumulic andosol, (6)	Grassland (Pasture)
26	Atsuta-Mura	A/B/C	Residual soil	Acid brown forest soil, (16)	Grassland (Meadow)
47	Tōbetsu-Cho	A/B/C2	Diluvial soil	Pseudo-gley soil, (16)	Grassland (Pasture)
51A	Atsuta-Mura	A/A/B/C1/C2	Diluvial soil	Pseudo-gley soil, (16)	Grassland (Meadow)
119	Tōbetsu-Cho	B/C1/C2	Alluvial soil	Brown lowland soil, (16)	Greenhouse field
126	Tōbetsu-Cho	A/B1/B2/C1/C2	Alluvial soil	Gley lowland soil, (16)	Rotational field

TABLE 2. Fundamental properties of soils

Soils[a]	Depth (cm)	Particle size distribution[b] Sand	Silt	Clay	Organic matter (%)	Bulk density (g/cm^3)	Void ratio
		(%)					
No. 1-Ap	0-16	38.5	40.5	21.5	10.3	0.94	1.71
A1	16-32	34.5	41.0	24.5	10.1	0.96	1.63
B	32-47	10.0	41.0	49.0	8.7	0.70	2.73
C	47-	17.0	40.5	42.5	5.6	0.75	2.49
No. 2-A	0-19	20.0	46.0	34.0	12.7	0.80	2.09
B	19-38	7.5	34.0	58.5	9.4	0.68	2.85
C	38-	13.5	36.5	50.0	6.2	0.82	2.28
No. 3-A	0-18	37.0	38.5	24.5	5.4	1.12	1.26
C	18-26	20.5	36.5	43.0	4.2	1.11	1.36
ⅡA	26-40	7.0	36.0	57.0	4.8	0.95	1.81
ⅡC	40-	9.0	43.0	48.0	3.3	1.02	1.64
No. 4-Ap	0-15	45.0	33.0	22.0	23.1	0.68	2.42
AC	15-28	38.5	41.0	20.5	23.2	0.62	2.72
ⅡAC	28-42	42.0	36.5	21.5	27.9	0.53	3.56
ⅢAC	42-60	27.5	30.5	42.0	19.2	0.65	2.83
ⅥA	60-78	31.0	36.5	32.5	15.3	0.76	2.35
ⅣC	78-	34.5	34.5	31.0	5.1	1.02	1.64
No. 26-A	0-20	61.0	16.5	22.5	3.0	1.44	0.85
B	20-45	59.0	24.5	16.5	1.4	1.36	1.01
C	45-	60.0	25.0	15.0	1.1	1.34	1.05
No. 47-A	0-21	27.5	38.5	34.0	5.5	1.28	1.03
B	21-35	20.0	37.5	42.5	2.7	1.27	1.19
C2	48-	21.5	37.0	41.5	0.7	1.35	1.05
No. 51A-A	0-15	35.5	48.0	16.5	4.9	1.19	1.19
A/B	15-29	38.0	43.5	18.5	4.4	1.18	1.22
C1	29-34	35.5	39.5	25.0	1.4	1.49	0.81
C2	34-	26.0	24.0	50.0	1.1	1.35	1.02
No. 119-B	8-20	42.5	36.5	21.0	5.3	1.20	1.19
C1	20-46	58.5	27.5	14.0	1.3	1.19	1.28
C2	46-	39.0	37.5	23.5	1.3	1.18	1.31
No. 126-A	0-19	28.5	34.0	37.5	7.7	0.83	2.13
B1	19-30	9.0	34.0	57.0	6.6	0.85	2.09
B2	30-39	9.5	30.5	60.0	3.0	0.98	1.80
C1	39-49	8.5	29.0	62.5	2.8	0.98	1.80
C2	49-	24.5	32.5	43.0	3.1	0.99	1.76

[a] Profile No. and Horizon [b] International system

2. Measurement of shrinkage of undisturbed samples

Undisturbed soil samples were taken in cylindrical metallic tins (5 cm in diameter, 2.5 cm in height) from each horizon of the profiles. The inside plane of tins were slightly greased with vacuum grease before use. Duplicated core samples were prewetted to saturation and then dried in the room air with temperature of 20±1°C. The mass and volume of core samples were determined at intervals of twelve hours in the course of drying. The determination of volume was made by measuring the length of diameter and height of cylindrical soil block. The diameter was measured by a travelling microscope on two positions at right angles and those measured values were averaged. The height was measured by a height gauge on four marked surface points and those measured values were averaged. Minimum lengths measured by the microscope and the gauge were 0.001 cm and 0.002 cm respectively. When the water lost during successive weighings became negligibly small (about 14 days from the starting), the core samples were oven-dried at 105°C and the mass and volume were remeasured.

3. Measurement of shrinkage of remoulded samples

Soil paste (remoulded sample) whose moisture content was equal to liquid limit was prepared. The remoulded sample was packed in a stainless steel dish (5 cm in diameter, 1.5 cm in depth) and dried at 20°C. The mass and volume of the remoulded sample were determined in the same manner as the case of the undisturbed sample.

Results and Discussion

1. Shrinkage behavior (Shrinkage curve and shrinkage type)

The shrinkage curves of undisturbed samples and remoulded samples of four soils are shown in Figs. 1 to 4.

These four soils showed the typical shrinkage behavior respectively. The volume reduction is expressed as a change of void ratio, and water content as a percentage of oven-dry mass. Void ratio is convenient for the comparison of undisturbed sample with remoulded sample as to the change of pore volume being produced by soil shrinkage (19, 21).

Although the remoulded samples of four soils shown in Figs. 1 to 4 differ from each other in initial water content and initial void ratio, all of their shrinkage curves have two shrinkage phases; normal shrinkage at initial stage of water loss and residual shrinkage at final stage.

While, four shrinkage curves of undisturbed samples are obviously different from each other. No. 4-IIAC soil (Fig. 1) shows two shrinkage phases.

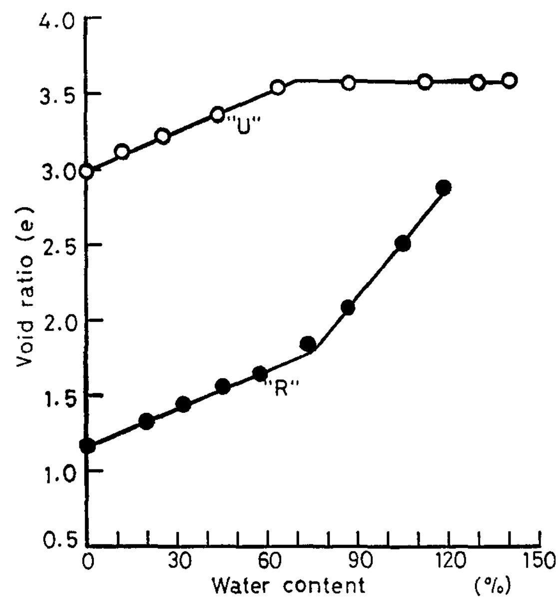

Fig. 1. Shrinkage curves of undisturbed sample and remoulded sample for No. 4-IIAC soil.
("*U*": Undisturbed sample, "*R*": Remoulded sample)

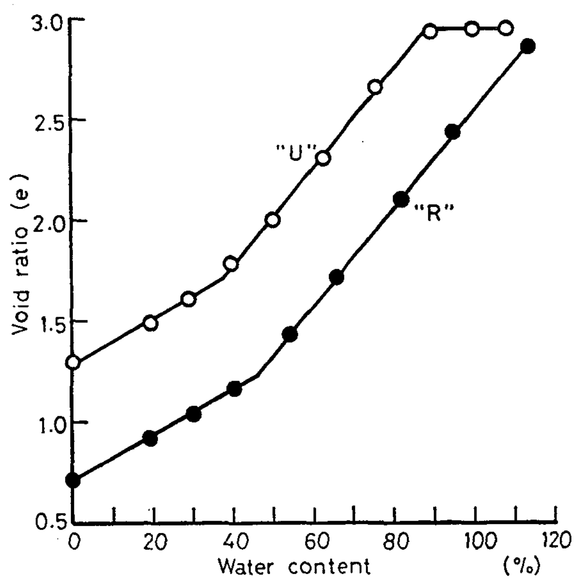

Fig. 2. Shrinkage curves of undisturbed sample and remoulded sample for No. 2-B soil.
("*U*": Undisturbed sample, "*R*": Remoulded sample)

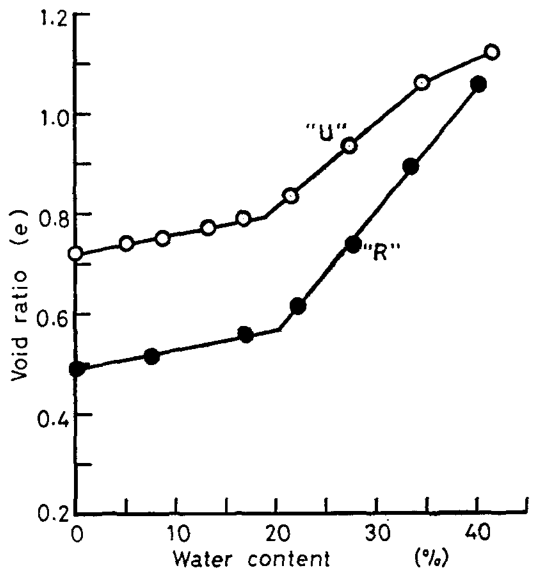

Fig. 3. Shrinkage curves of undisturbed sample and remoulded sample for No. 47-C2 soil.
("*U*": Undisturbed sample, "*R*": Remoulded sample)

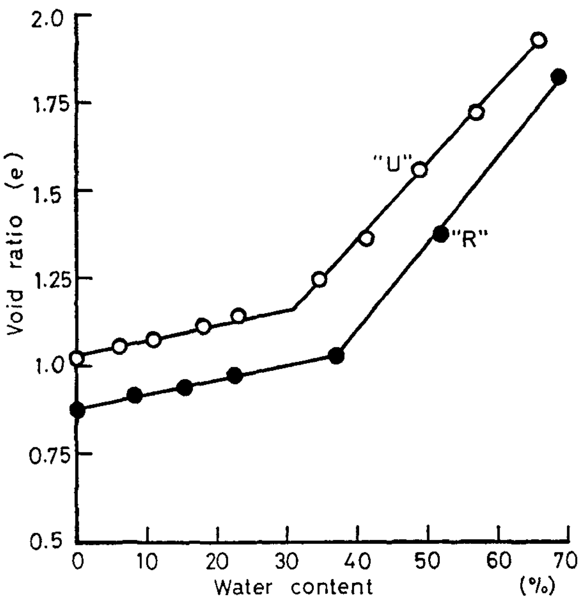

Fig. 4. Shrinkage curves of undisturbed sample and remoulded sample for No. 126-B2 soil.
("*U*": Undisturbed sample, "*R*": Remoulded sample)

One has no volume change at the initial stage of water loss, and the other resembles the residual shrinkage phase of remoulded sample with respect to the slope of shrinkage line. Hence, the former corresponds to structural shrinkage, and the latter to residual shrinkage. Consequently, the feature of this shrinkage lacks normal shrinkage phase. We designated this shrinkage type as type I. No. 2-B soil (Fig. 2) showed three shrinkage phases, structural shrinkage, normal shrinkage, and residual shrinkage. This shrinkage type have been considered to be most general in the shrinkage of undisturbed samples, was designated as type II. No. 47-C 2 soil (Fig. 3) has also three shrinkage phases, but it differs from type II in that the volume change occurs at initial shrinkage phase (structural shrinkage). We designated this shrinkage type as type III. No. 126-B 2 soil (Fig. 4) has two shrinkage phases similar to those of the remoulded sample (normal shrinkage and residual shrinkage). This shrinkage type, termed type IV, has no structural shrinkage.

As described above, the shrinkage type of undisturbed sample was classified into four kinds from type I to IV. In each shrinkage type, the manners of appearance of shrinkage phases from the initial stage of water loss are summarized as follows:

Type Ⅰ : Structural shrinkage without volume reduction→Residual shrinkage

Type Ⅱ : Structural shrinkage without volume reduction→Normal shrinkage→Residual shrinkage

Type Ⅲ : Structural shrinkage with volume reduction→Normal shrinkage→Residual shrinkage

Type Ⅳ : Normal shrinkage→Residual shrinkage

The shrinkage types and total shrinkage values of undisturbed samples are shown in Table 3. Total shrinkage values were expressed by percentage of initial volume.

Soils which had shrinkage type I are most of the surface or burid surface soils of volcanic ash soil and three soils (No. 51 A) of nonvolcanic ash soil. In soils of type I the total shrinkage values have a tendency to be smaller in comparison with values of soils of other shrinkage types. This attributes to have not normal shrinkage phase. The most soils (seventeen) from various horizons of volcanic ash and nonvolcanic ash soil belong to shrinkage type II. It means that this type is most typical in the shrinkage of undisurbed samples. Total shrinkage values ranged widely from 5.1 to 40.1%, and in general, the values of volcanic ash soils are larger than those of nonvolcanic ash soils. The shrinkage of calyey soil has been discussed and clarified to

TABLE 3. Soils included under each shrinkage type and total shrinkage of undisturbed samples

Shrinkage type	Soils and total shrinkage[e]
I[a]	No. 1-Ap (6.3) No. 1-A1 (7.5) No. 2-A (14.3) No. 3-A (2.8) No. 4-Ap (6.9) No. 4-AC (8.3) No. 4-IIAC (13.0) No. 51A-A (2.5) No. 51A-A/B (1.9) No. 51A-C1 (1.9)
II[b]	No. 1-B (30.4) No. 1-C (24.7) No. 2-B (40.1) No. 2-C (21.3) No. 3-C (7.9) No. 3-IIA (23.8) No. 3-IIC (18.0) No. 4-IIIAC (26.7) No. 4-IVA (23.6) No. 4-IVC (17.7) No. 26-A (6.1) No. 26-B (7.5) No. 47-A (8.8) No. 119-B (5.1) No. 119-C1 (5.8) No. 119-C2 (5.4) No. 126-A (10.4)
III[c]	No. 26-C (11.4) No. 47-B (17.3) No. 47-C2 (18.4) No. 51A-C2 (23.2) No. 126-B1 (32.5)
IV[d]	No. 126-B2 (30.9) No. 126-C1 (29.7) No. 126-C2 (30.9)

[a] Structural shrinkage without volume reduction→ Residual shrinkage
[b] Structural shrinkage without volume reduction→ Normal shrinkage→ Residual shrinkage
[c] Structural shrinkage with volume reduction→ Normal shrinkage→ Residual shrinkage
[d] Normal shrinkage→ Residual shrinkage
[e] Figures indicated in parentheses : the values are given by $(1-V_f/V_0)\times 100$, where V_0 and V_f are initial volume at saturation and final volume at oven-drying, respectively.

depend on not only the amount of clay but its nature (22, p. 154). Therefore, the large total shrinkage values observed in volcanic ash soils must be due to the nature of allophane with large amount of swelling-water (7). Shrinkage type III and IV were observed only in the subsoils of nonvolcanic ash soils. Especially all subsoils belonging to type IV were from No. 126 which was gley soil with heavy texture and poor drainage. Total shrinkage values of type IV were larger than those of type III. This may be explained by the fact that the shrinkage phase of type IV has normal and residual shrinkage and does not have structural shrinkage.

As described above, it became clear that all soils from volcanic ash soil belong to the shrinkage type I or II which posseses a clear structural shrinkage phase. From these results it is inferred that the structure of volcanic ash soils used in this study is well-developed.

2. Index of structural development

In Figs. 1 to 4, the final void ratio which corresponds to void ratio at the end of shrinkage (at oven-dry) is larger in the undisturbed sample than remoulded sample of the same soil. This tendency is independent of the shrinkage types. In the shrinkage type I to III the shrinkage of undisturbed sample have a structural shrinkage phase which decreases volume reduction, consequently the final void ratio of undisturbed sample increases. While, the shrinkage type IV does not have a structural shrinkage phase. Nevertheless the final void ratio of undisturbed sample is larger than that of remoulded sample. This is due to the fact that the slope of normal shrinkage line is generally smaller in undisturbed sample than remoulded sample (21).

In Figs. 1 to 4, the difference between the final void ratio of undisturbed sample and that of remoulded sample varies with shrinkage types, that is, the difference in type I is fairly larger than that in type IV. This may indicate that the structural development of a soil can be evaluated by comparing the final void ratio of undisturbed sample with that of remoulded sample of the same soil. In regard to such a structural index, the difference of both final void ratios or the ratio of one void ratio to other void ratio may be considered. We chose to use the latter (ratio), considering that the relation between void ratio (e) and porosity (n) is not directly proportional, but exponential (Fig. 5).

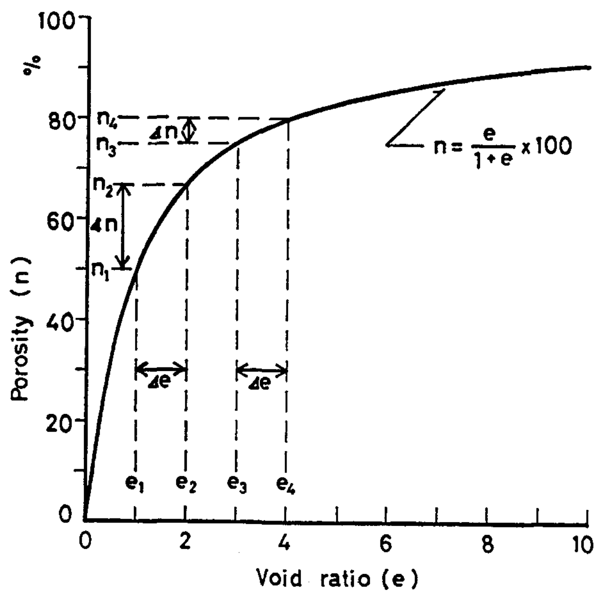

Fig. 5. Relation between porosity (n) and void ratio (e).

TABLE 4. Final void ratio, Coefficient of structural development and shrinkage type

Soils	Final void ratio: Undisturbed sample $(e_f)_U$	Final void ratio: Remoulded sample $(e_f)_R$	Coefficient of structural development[a] $(e_f)_U/(e_f)_R$	Shrinkage type
No. 1-Ap	1.485	1.071	1.39	I
A1	1.465	0.943	1.55	I
B	1.567	0.784	2.00	II
C	1.656	0.873	1.90	II
No. 2-A	1.617	0.952	1.69	I
B	1.301	0.726	1.79	II
C	1.612	0.922	1.75	II
No. 3-A	1.225	0.827	1.48	I
C	1.194	0.611	1.95	II
II A	1.189	0.598	1.99	II
II C	1.208	0.677	1.78	II
No. 4-Ap	2.145	1.199	1.79	I
AC	2.440	1.263	1.93	I
II AC	2.987	1.139	2.62	I
III AC	1.952	0.943	2.07	II
IV A	1.637	0.876	1.87	II
IV C	1.364	0.802	1.70	II
No. 26-A	0.845	0.562	1.50	II
B	1.009	0.615	1.64	II
C	0.936	0.636	1.47	III
No. 47-A	0.916	0.572	1.60	II
B	0.821	0.517	1.59	III
C2	0.727	0.475	1.53	III
No. 51A-A	1.138	0.736	1.55	I
A/B	1.247	0.744	1.68	I
C1	0.796	0.545	1.46	I
C2	0.612	0.453	1.35	III
No. 119-B	1.092	0.757	1.44	II
C1	1.220	0.656	1.86	II
C2	1.190	0.645	1.84	II
No. 126-A	1.879	0.849	2.21	II
B1	1.117	0.800	1.40	III
B2	1.023	0.874	1.17	IV
C1	0.974	0.783	1.24	IV
C2	0.848	0.718	1.18	IV

[a] C_{sd}

In Fig. 5, when we give following values to void ratios; $e_1=1$, $e_2=2$, $e_3=3$, and $e_4=4$, their corresponding porosities are $n_1=50$, $n_2 \fallingdotseq 66.7$, $n_3=75$, and $n_4=80$.

Firstly, we take the difference in void ratios,

then $(e_2-e_1)=(e_4-e_3)=1$

whereas $(n_2-n_1)>(n_4-n_3)$

From the above relations, it is evident that even though the differences in void ratios are equal, the corresponding differences in porosities are not equal.

Nextly, we take the ratios of void ratios,

then $e_2/e_1(=2)>e_4/e_3(\fallingdotseq 1.33)$

This relation equals to the relation of difference in porosities.

From the results described above, we propose the "Coefficient of structural development (C_{sd})" on the index to express numerically the structural development of a soil:

$$C_{sd}=(e_f)_U/(e_f)_R \qquad [1]$$

where

C_{sd}=Coefficient of structural development
$(e_f)_U$=Final void ratio of undisturbed sample
$(e_f)_R$=Final void ratio of remoulded sample

When the C_{sd} value of a soil is equal to 1.0, it means that the structural development of the soil is not recognized at all. When the C_{sd} value becomes greater than 1.0, the structural development of soil is better. Table 4 shows the final void ratios of undisturbed samples and remoulded samples, C_{sd} values, and shrinkage types of all soils.

The C_{sd} values ranged widely from 1.17 to 2.62, and generally, the values of volvanic ash soils are larger than those of nonvolcanic ash soils. As for the relation between C_{sd} values and shrinkage types, generally speaking, the C_{sd} values of soils with shrinkage type I and II are large compared to those of soils with shrinkage type III and IV. Accordingly, it is evident that as the structural shrinkage phase of undisturbed sample is clear, the structure of the soil is generally well-developed.

3. Physical meaning of index

In order to clarify the physical meaning of C_{sd}, the porosity of undisturbed sample was classified on the basis of shrinkage behavior. The idea is schematically illustrated in Fig. 6.

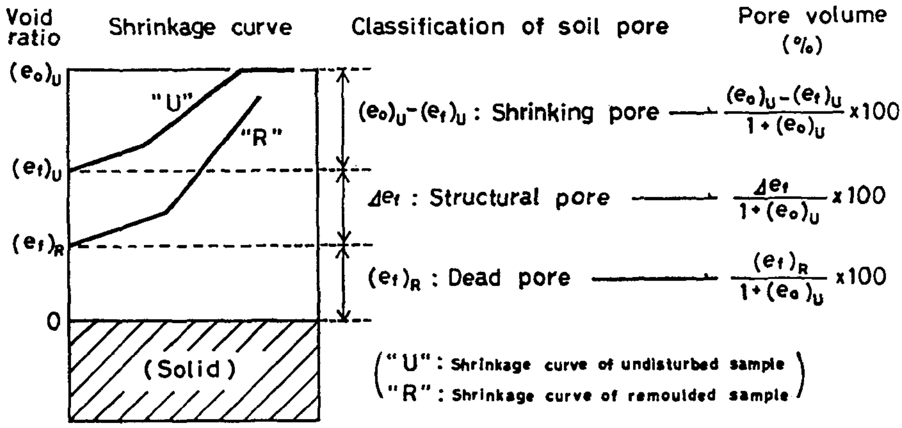

Fig. 6. Classification of pore volume of undisturbed sample on the basis of shrinkage behavior.

By using three void ratios, initial void ratio of undisturbed sample $(e_0)_U$, final void ratio of undisturbed sample $(e_f)_U$, and final void ratio of remoulded sample $(e_f)_R$, the total pore of undisturbed sample at sampling time is classified into three kinds of pore; shrinking pore, structural pore, and dead pore.

Shrinking pore is defined as the pore lost by volume reduction of undisturbed sample during drying from saturation to oven-drying, and therefore, it is equal to the total shrinkage value of each soil in Table 3. This pore is considered to be the pore occupied by the soil water in a swelling state and to be the unstable pore to drying in comparison with two other pores. Shrinking pore is calculated from the following equation using the initial void ratio and final void ratio of undisturbed sample:

$$p_{(\text{shrinking})}=\frac{(e_0)_U-(e_f)_U}{1+(e_0)_U}\times 100 \qquad [2]$$

where $(e_0)_U$=initial void ratio of undisturbed sample

Shrinking pore is termed the "variable-volume" pore by YULE and RITCHIE (23).

Structural pore is defined as the pore which resisted to the volume reduction due to dehydration. The resistence arises from the structure formed under the field condition. This pore is considered to be the pore occupied by the soil water lost mainly at the structural shrinkage phase and to be the largest pore in pore size in comparison with two other pores. Structural pore is given by the following equation using the difference (Δe_f) between final void ratio of undisturbed sample and that of remoulded sample:

$$p_{(\text{structural})}=\frac{\Delta e_f}{1+(e_o)_U}\times 100 \qquad [3]$$

Dead pore is defined as the pore corresponding to the shrinkage limit due to total shrinkage of remoulded sample, as pointed out by YONG and WARKENTIN (22, p. 167). This pore is considered to be the pore at the closest packing and to be the pore depending on the soil particle nature other than soil structure. Dead pore is given by the following equation using the final void ratio of remoulded sample $(e_f)_R$:

$$p_{(\text{dead})}=\frac{(e_f)_R}{1+(e_o)_U}\times 100 \qquad [4]$$

Equation [1] is transformed as follows:

$$C_{sd}=(e_f)_U/(e_f)_R=[(e_f)_R+\Delta e_f]/(e_f)_R$$
$$=1+\Delta e_f/(e_f)_R \qquad [5]$$

where $\Delta e_f=(e_f)_U-(e_f)_R$

From equation [5], C_{sd} value is decided by Δe_f and $(e_f)_R$. On the other

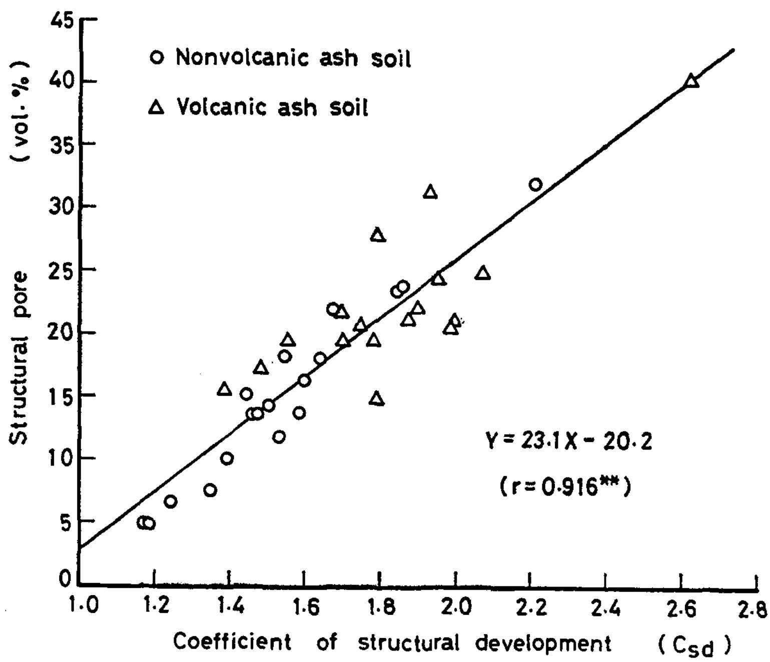

Fig. 7. Relation between structural pore volume and C_{sd} (Significance level: $^{**}p=0.01$).

hand, Δe_f relates to the structural pore from equation [3]. Accordingly, it is expected that there is a positive relation between C_{sd} values and structural pores. In fact, C_{sd} is nearly directly proportional to the structural pore as shown in Fig. 7. And the coefficient of correlation ($r=0.916$) is highly significant (0.01 level).

From Fig. 7, it is obvious that C_{sd} value increases with increasing of structural pore. And this is the physical meaning of C_{sd} proposed here.

4. Relation with morphological soil structure

As the types of morphological soil structure observable in the fields, there are granular, blocky, prismatic or columnar, platy, and massive structure. In characterization of soil structure, these are most fundamental. Therefore, it will be necessary to clarify the relation between morphological soil structure and C_{sd}. For some soils whose morphological soil structure were clearly distinguished at sampling time the relationship was examined and is shown in Table 5.

TABLE 5. Relation between morphological soil structure and C_{sd}

Morphological structure	Soils	Coefficient of structural development (C_{sd})	Shrinkage type
Granular	No. 4-Ap	1.79	I
	No. 4-AC	1.93	I
	No. 4-II AC	2.62	I
	No. 26-A	1.50	II
	No. 126-A	2.21	II
Blocky	No. 1-B	2.00	II
	No. 1-C	1.90	II
	No. 2-B	1.79	II
	No. 47-B	1.59	III
	No. 119-B	1.44	II
	No. 119-C1	1.86	II
	No. 119-C2	1.84	II
Massive	No. 47-C2	1.53	III
	No. 51A-C2	1.35	III
	No. 126-B2	1.17	IV
	No. 126-C1	1.24	IV
	No. 126-C2	1.18	IV

C_{sd} values for the soils with granular structure range from 1.50 to 2.62, for blocky structure from 1.44 to 2.00, and for massive structure from 1.17 to 1.53. Although the range of C_{sd} values for the same structure type are fairly wide, it was obvious that C_{sd} values have a tendency to increases according to the order of massive structure, blocky structure, and granular structure. Also, it was recognized that the soils of granular structure belonged to shrinkage type I or II, those of blocky structure belonged to type II or III, and those of massive structure belonged to type III or IV.

From these results, it was concluded that there is a certain relationship between C_{sd} values and the types of morphological structure observed in the fields.

In this study, the structural development of a soil was mainly discussed. The stability of soil structure is the subject for a further study.

Summary

The shrinkage behavior of undisturbed core samples and remoulded samples of thirty-five clayey soils collected from nine soil profiles of different soil types was examined and related to the structural development of each soil.

Shrinkage curves of undisturbed samples were classified into four types from the difference in the manner of appearance of three shrinkage phases (structural, normal and residual shrinkage).

On comparing the shrinkage curve of undisturbed sample with that of remoulded sample of the same soil, the void ratio at the end of shrinkage produced by oven-drying (final void ratio) was larger in undisturbed sample than remoulded sample.

As an index to evaluate numerically the structural development of a soil, the "Coefficient of structural development (C_{sd})" was proposed. C_{sd} was defined as the ratio of final void ratio of undisturbed sample to that of remoulded sample. C_{sd} values ranged widely from 1.17 to 2.62, and in general, the values of volcanic ash soils were larger than those of non-volvanic soils, so it was recognized that the structure of volcanic ash soils is generally well-developed.

Based on the shrinkage behavior the total pore of undisturbed sample at sampling time was classified into three kinds ; shrinking pore, structural pore, and dead pore. C_{sd} values were nearly in proportion to the structural prove volumes.

C_{sd} showed a certain relation with the morphological soil structure (granular, blocky and massive structure) observed in the fields.

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