

PARTICLE INTERACTION IN SOIL PHYSICS

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The most important problems in soil physics concern the fluxes of water, gases, molecules and ions in soils. These fluxes occur in the voids in soils, and so it becomes necessary background in formation to know the size, shape, and stability of these voids. This requires an understanding of soil structure, which in turn requires an understanding of the particle interaction that leads to the soil structure we see in the field or study at different levels of magnification in the laboratory. So particle interaction is closely related to the important problems of fluxes of materials in soils.

In engineering applications, the interest is in the reaction of the soil mass to an applied stress, that is the stress-strain relationship for a particular soil. This is determined by soil structure which is determined again by particle interaction. Soil structure includes the size, shape and arrangement (fabric) of soil particles and voids.

Particle interaction, as defined for this paper, will include the arrangement of particles as well as the forces between particles. It is this interaction which results in the structure of the soil, and an understanding of soil structure requires an understanding of particle interaction. Unfortunately, the forces of particle interaction, especially the forces of attraction between particles, are not well understood. This is partly because methods have not been developed for study of particle interaction at the level at which this interaction must be studied, and partly because most of the emphasis in soil physics is on the important practical

problem of fluxes of materials through the soil. This paper is a review of some of the aspects of particle interaction which are important in determining soil structure, with mention of some of the applications which have been made in soil physics of particle interaction studies.

1. Organic-Inorganic Interaction

The interaction of organic molecules with inorganic surfaces is the dominant particle interaction leading to soil structure in surface horizons of most soils. The importance of maintaining organic matter in soils by using appropriate cropping systems is because of this effect on soil structure through particle interaction. While returning organic matter to the soil has been a recognized goal for soil management, the organic component of soils is often neglected in soil physics studies. The importance of organic matter has been stated by G. V. Jacks (1963) as follows: "The union of mineral and organic matter to form of organic mineral complex-a synthesis as vital to the continuance of life as, and less understood than, photosynthesis...".

Many of the early studies in soil physics related organic matter content to general physical properties. However, an understanding of particle interaction is difficult to obtain in this way, and recent studies on mineral organic particles as important units of the soil will lead to increased knowledge about the organic-inorganic interaction. In many soils, it is these mineral-organic particles which should be

studies as the ultimate units of soil rather than soil grains with organic matter removed. It is known that the bulk density of these mineral-organic units increases as the size decreases (Gumbs and Warkentin, 1976). Mineral organic units can also be separated on the basis of density rather than on the basis of size. **Table 1** shows some characteristics of these units, indicating the large difference in composition of the fractions of different densities.

Table 1 Properties of mineral-organic particles separated from soil on the basis of density (Spycher, 1977).

Density g cm ⁻³	Organic carbon, %	Nitrogen %	Amorphous Fe ₂ O ₃	Oxides Al ₂ O ₃
<1.7	24	2.3	13.4	20.4
1.7-1.8	36	1.7	15.1	16.0
1.8-1.9	30	1.4	17.7	8.5
>1.9	11	0.8	12.1	6.1

2. Level of Observation of Soil Structure

Soil structure can be viewed at different levels of magnification, ranging from the peds which can be described in field soils down to features in the 1-10 nm range which must be examined with an electron microscope. The different levels of structure, and levels at which particle interaction takes place, determine different properties of the soil (**Table 2**). The largest voids, in the 10⁴-10⁶ nm range, are called interpedal voids. At the large end of

the range, these include soil cracks. It is in these voids where the fluxes of water, air, dissolved and suspended materials take place. At the 10⁴ to 10² nm range are the voids that hold water available for plant growth. These voids are between clusters that form the structural units that make up the peds. The clusters, in turn, are composed of domains. The interdomain voids in the range of 10-100 nm are determined by forces between particles. The intergrain forces determine the voids in the 1-10 nm range. These different levels of soil structure are summarized in **Table 2**.

An example of the differences in interparticle forces at different levels of structure is provided in recent studies by Sakuma (1977). He separated water stable aggregates from total aggregates of a certain size. The water stable aggregates had a large volume of voids in the 3 nm range, but very few voids in the 10-30 nm range (Figure 1). Aggregates which were not stable to sieving in water had voids in the 10-30 nm range, but a lower volume in the 3 nm range. The water stable aggregates from this soil had a surface area of 27.1 m² g⁻¹ and a bulk density of 1.77 g cm⁻³, compared with 24.3 m² g⁻¹ and 1.73 g cm⁻³ for the total sample including non-stable aggregates. Interaction at a high level of magnification determines property such as aggregates stability which is measured at the level of field observation.

Table 2 The sizes of structure units or voids of importance in soils.

nm	Size	Other	Name	Processes
1-10		10-100A	Intergrain	Particle forces
10-100		100-1000A	Interdomain	Particle forces
10 ² -10 ⁴		0.1-10 ^μ	Intercluster	available water
10 ⁴ -10 ⁵		0.01-0.1mm	Interped	fluxes
10 ⁵ -10 ⁶		0.1-1mm	Interped	cracks

3. Grouping of Soils Based Upon Particle Interaction

One of the obvious manifestations of particle interaction in soils is volume change - swelling on wetting and shrinking on drying. This phenomenon of volume change can be used to group soils on the basis of type of particle interaction. Soils which show no overall volume change, for example sands, have particle interaction which is characterized by friction forces, but very low levels of surface forces of attraction and repulsion. The second group of soils, the swelling clays, show reversible volume change where the particle arrangement and particle interaction can change reversibly with change in water content. A third group of soils shows irreversible volume change, for example, "quick" clays and allophane soils. Here the particle interaction changes irreversibly as the soils are dried. Rewetting does not produce swelling back to the initial undried condition.

The fluxes of water and other materials must be described using different models for these different groups of soils. For example, if a constant geometry cannot be assumed, a moving coordinate system can be used in describing infiltration into reversibly swelling soils (e.g. Smiles and Rosenthal, 1968). Water infiltration into swelling soils depends upon the large voids formed during cracking, and this must be taken into account in the description of the process (Warkentin, 1974).

The suitability of clay soils for mole drains is another application of particle interaction. The particle attraction is sufficiently strong in some cases to create a stable structure which will maintain a drainage channel. In other soils, the clay disperses more easily and this drainage channel disappears within one or two seasons. The susceptibility of soils to erosion also depends upon particle interaction.

The soils which are most erosive are those where interparticle attraction is not very large.

4. Interparticle Bonds

Soil structure formation processes are different depending upon the particle interaction for the particular soil and the interparticle bonds in that soil. It is easy to list the various organic and inorganic bonding mechanisms which can take place in soils, but it is difficult to study quantitatively the effects of different kinds of bonding. The possible bonds have been reviewed by Greenland (1968) and studies of cementing by iron and aluminum hydroxides have also been published.

A method of calculating the forces of attraction in swelling clays has been presented by Warkentin (1976) based on an analysis of the water retention curves for soils. Since the water retention curve is the net resultant of forces of attraction and repulsion, and since the force of repulsion can be calculated under certain assumptions, it is possible to calculate the force of attraction. Another use of this method is to calculate the bonding which has been induced by compacting samples in different ways.

Another method of obtaining information on interparticle bonds is to calculate the activation energy of bonds from the rheological behavior of soil. This has been done by Murayama and Shibata (1961) and Mitchell (1976). The results show that the activation energy required to break bonds and achieve new equilibrium positions of soil particles is about 35 kcal mole⁻¹, about an order of magnitude higher than the interparticle bonding for water. These measurements also show that the number of bonds increases with decreasing water content of the soil, changing by about two orders of magnitude from wet to dry soil. Typical values show increases from 10¹⁰ to 10¹²

Table 3 Measured interaction volume and liquid limit of representative clays

	Interaction Volume	Liquid Limit with Saturating Cation	
		Na	Ca
Clay	cc/g		
Kaolinite	0.5	47	54
Illite	2	61	90
Montmorillonite	25	950	360
Allophane	—	180	180

bonds per square centimeter.

5. Interaction Volume

The concept of an interaction volume determining bulk density, sediment volume, water content at the liquid limit, etc. has been used in many applications. The interaction volume is determined by particle interaction, both repulsion and attraction, and the resulting soil structure. Warkentin (1961) discussed the application of interaction volume to the liquid limit of clays.

Table 3 shows the effect of surface area and of exchangeable cations on liquid limit and on interaction volumes measured as sediment volumes under defined settling conditions. The water content (or soil volume) at the liquid limit is determined by forces of attraction for kaolinite and illite, as shown by the higher liquid limit for Ca-clays. In montmorillonite, repulsion is the dominant force. Exchangeable cations have only a minor influence on interparticle forces in allophane. The concept of interaction volume has been useful in studying properties of sediments as well as properties of soils. The structure and bulk density of vertisols is related to this interaction volume.

6. Index Properties for Particle Interaction

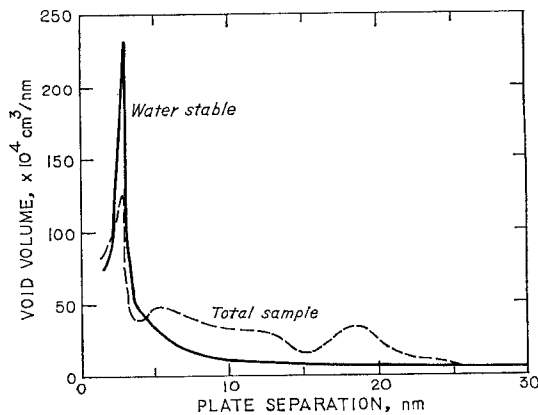
Particle interaction is difficult to measure, and hence index properties have been used in this characterization as they have in other areas of soil physics. Grain-size distribution

is not an adequate index property for particle interaction, but many properties such as those listed in **Table 4** have been used. Plasticity

Table 4 Index properties for particle interaction in soils.

Plasticity
Emerson Coherence Test
Shear Properties
Sediment Volume
Volume Change-Swelling Pressure
Surface Area

is very widely used in engineering characterization of soils as a measure of particle interaction. Liquid limit and plastic limit are measured and the plasticity index is calculated. Plasticity has not been as widely used as an index property in agricultural soils, even though the Atterberg limits were first suggested for classification of agricultural soils. However, it has been argued (Warkentin, 1972) that for soils with more than 30% clay, plasticity is a more useful index property than is grain-size distribution.

**Figure 1**

The Emerson Coherence Test (Emerson, 1969) is a measure of the interaction of particles when a soil aggregate is immersed in water. This is a direct index of particle interaction and is also used as a classification for soil structure. The relative value of cohesion and friction parameters in the shear test is an index property of particle interaction. Other interaction properties such as sediment volume, swelling, and surface area have been discussed above.

7. Summary

In this brief review, I have attempted to show the importance of interparticle forces in determining physical properties of soils. Since most physical properties depend upon soil structure, they are determined by interparticle forces. Several examples are discussed to illustrate these points. Unfortunately, our knowledge of interparticle forces is very superficial. In order to understand physical properties we will need to increase our knowledge of interparticle forces. This will require more powerful methods than those which we now use. Possibly some of the methods now being used to study surfaces of metals and polymers can be applied to our studies in soil physics.

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Questions and Answers

Iwata: I'd like to ask you two questions. First, Dr. Kobayashi, who is here, showed that the plant root takes a very important role in the formation of soil aggregate. How do you think about this? Second, you showed the liquid limit of allophane is independent to the kinds of cation. You said this is mainly due to the properties of allophane. Please explain this more in detail.

Warkentin: The first question on the influence of roots on structure, I have to agree with that, because roots have a number of influences; they have a drying influence, they have a pressure influence. The roots produce organic materials which give you an initial stabilization of structure. It does not worth very long but you get an initial stabilization in this way. And certainly part of the difference that we seen between surface soil and subsoil is due to the influence of plant roots; the larger changes. Many of these, of course, are physical changes of wetting and drying of pressure exerted, although we know that if we exert the same pressure on an aggregate that the root does, we do not get the same kind of

aggregate in a soil. So it is more that just a physical phenomena. In addition to that, we have the production of organic materials which are very important. So, I think that in terms of creating structure for very many soils this is important. In the soil of very high clay content versus soil, it is probably less important, that is, because you get such a large volume change and it becomes dominant over the effect of the root. But over the range of soil that we normally use in agricultural production, the roots certainly have a large influence on the kind of aggregate structure which we have, how stable it is. On the second question I think you are better able to answer it than I am. And I would like to hear a discussion on this. Firstly, the allophane is a constant potential rather than a constant charged surface and so we have a very different influence of the saturating cation on this. So we have first of all a small charge certainly a small surface charge and I think that is a main influence, main reason, why we find a very small influence of the cation.

You agree with that?

Iwata: Thank you very much.

Kobayashi: I ask you in relation to the action of roots for the better stability of the aggregate. I think that the excreted material from the roots during it's metabolism may be contributing to the aggregation which might be caused by the coating of thing of grain, and the excreted materials make them cohere and lead to good stability, and the excreted material, I think to be pectic substances. I'd like to ask you if pectic material would be helpful for the larger stability of the aggregate. (Interpreted by Mr. Hুরুkawa)

Warkentin: I can not answer your question in detail, because I am not a good enough organic chemist or micro-biologist. Certainly there is a lot of coating of aggregate from these materials that are given off and the roots

give off a lot of material while they are growing. Because as the root is growing a lot of material is falling off from the outside. And this has very high aggregating properties. My impression is that it is only for maybe two months, three months, something like that because these materials again break down further and so the coating you have only initially and so either you must always add new coating or you must create molecules that are more stable and these are generally the decomposition products which are then absorbed into the aggregate a very union of clay and organic matter and the long terms stability, I think, it's due to these molecules that are much more resistant to the composition because they are either trapped between the particle surfaces and hence not exposed to enzymes which can move into the system, or they are units which are more stable. If anybody else has any information on this, I would be glad to have it. I have not myself made a detailed study of that but in most soils this is how I understand what is happening that the root material is very important in a short term but less important in a long term.

Sudo: What is the meaning of the term interaction volume? I want you to show me some application of the term.

Warkentin: Interaction volume is not a theoretically well defined term, although in practice it turns out to be very useful. Let me give you one example first, and then we will discuss interaction volume a little more. I have been involved in the last two years in a problem of mine waste disposal and this is material where in the process they use sodium hydroxide to gain material out of the sand-clay mixture. And so you have a dispersed flurry which comes out the pipe and it makes a great big lake of dispersed clay. Now we want to settle the material out of that lake and

the settling and the density to which that material will settle depends very much on the kind of clay which you have. And because of the dominant influence of montmorillonite, what we were able to do was to map their ore body, determine the montmorillonite content of the clay and then tell them how much settling area they would need in order to dispose of the waste. This is one application of an interaction volume. Basically it is the volume of the solid particle plus the water around it which is retained around it under certain condition of settling. And these conditions vary with the worker. Some people just put it in a tube and let it settle under gravity and some people centrifuge it to bring it down. You can consolidate it under a certain given state of pressure. You can do many of these things but always you'll find a volume which the inorganic; the solid soil grain and it's associated water have a certain volume which you must deal with.

Sudo: Is it the volume per unit?

Warkentin: Yes, per unit volume or per unit weight usually solid, usually given as cubic centimeters per gram of solid. It gives you information about the different activity of material. If you have a very high interaction volume, you know you have a small strength. You have a low compactibility. You have other physical properties associated with that. Is that an answer to your question or can I be more specific than that?

Sudo: Thank you.

Nagota: May I ask you one question? How do you use the term of aggregate and the ped? What do you think about the difference between aggregate and ped?

Warkentin: You have asked a very embarrassing question for anyone working in soil structure because we are very careless with the term that we use in soil structure. And part of the problem that we have in communi-

cating is that we all use different words for the same thing. The way in which I use the word is that a ped is any unit of natural structure. I use it in a way which Bruwer has defined it. Do you know Bock Bruwer Fabric and Mineral Analysis of Soil? Bruwer came from Australia. This is how I use the term ped. Aggregate, when I talk about surface soil, the rounded unit of surface, the crumb (the English expression crumb) of surface soil. This is how I use the term aggregate. But I am not always consistent in that. But I think it would be worth our effort sometime, maybe in the international society of soil science, to have a look at the terminology of soil structure. And the slide which I put on with the different levels of structure, giving names to different levels, is a start on an attempt to do that. Bruwer, in his book, has done some of that, but I think we now need to go further and to agree on the use of certain term. But it is a real problem and my only use is, ped is a general term and an aggregate is a ped of the surface, plow layer of a soil. How do you use the term?

Nagota: Usually I was very confused.

Warkentin: So was I.

Nagota: I am going to distinguish them.

Warkentin: Thank you. It would be interesting to see whether this distinction becomes useful in practice. It is not only in soil structure, of course, soil water when through the same thing in terms of potentials, suctions and so on. It turns out that you can standardize some of this. I first become interested in this largely as an exercise. I wanted to see whether I could get way from using the term moisture in soil. And it turns out you can except when you want to talk about a soil which is a little bit wet. Then I still use the term moist. Otherwise I talk about soil water. Now some people say the distinction between water and moisture is that we're talking about a soil solution. I am not

sure I am prepared to buy that but I would have to listen to people like yourself and Prof. Gardner on it, but I think soil structure is the same thing. If we discipline ourselves not to use a range of terms, then I think we can give one term a certain meaning and then keep an other meaning for another term. But I think we must consciously discipline ourselves to do that there is no need to talk about soil moisture and soil water. One term is good enough, so let us define it and then if we need to, use the other term for something else. Does anyone else have any ideas on this very important problem of terminology because it is a key element in how we communicate? In soil water it is much easier, you can write an equation. In soil structure, you must use a word and it is very much harder to communicate the words than mathematic symbols. I would like to hear an idea from Prof. Gardner.

Gardner: I do not know what you mean with respect to a ped and an aggregate or not. I am not the right man to ask that question because I have assumed that a ped is a very large aggregate. And you can see that we use it as physicists more carelessly than the people in soil classification genesis because my colleges are quite clear in their own mind what the ped is. And I think they are clear as to an aggregate but I'm not sure. But I think that Dr.

Warkentin's suggestion of an international committee is well in order and perhaps since his country be the host of the next meeting. This commission might, the Japanese, might formally request on that occasion that such discussion be started because those of us who want to use these terms and would like to them correctly. Many of us are not so concerned what the term is if you just tell us which one to use. And this was the experience with the soil water. The terminology committee has been extremely valuable. Obviously you do not solve all of the problems at once, but the experience of the examining of terminology is that you find that your terms must keep up with your advanced knowledge. And they do get out of date. I think what Dr. Warkentin's lecture has shown all of us is that the terms we have learned are out of date. And the new terms must be worked out because they involved both ideas and language. And even though the language might end up to be English, in many cases, we've become aware that the choice is correct English words depend very much on what that means in other languages. And therefore whether it might be six words equally satisfactory to one in English. One of those is usually better than other when we come to translate it into several languages. That is a philosophical non-answer.