# Cohesion Development in Disrupted Soils as Affected by Clay and Organic Matter Content and Temperature[1]

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## ABSTRACT

Soils were dispersed and separated into sand, silt, and clay fractions that were reconstituted to give mixtures of each soil with 5 to 40% clay. In the range from 0 to 35% clay, higher clay contents resulted in greater stability. Rate of cohesion recovery was over 10 times as fast at 90°C as it was at 23°C, showing that the processes involved are physical-chemical rather than biological. Maximum rates of cohesion recovery occurred at moderate soil water tensions, probably because some tension is needed to pull the particles into direct contact, but a continuous water phase is also essential to allow diffusion of bonding agents to the contact points. Since diffusion rates in water increase 300%, while rate of cohesion recovery increased 1000% when temperature was raised from 23 to 90°C, other factors, such as higher solubilities at higher temperatures of compounds contributing bonding ions to the solution, probably play a role in the rate of cohesion recovery. Recovery of cohesion was more rapid in the soil with organic C contents of 0.004 kg/kg than in the soil with 0.012 kg/kg. When the organic matter was removed with $H_2O_2$ from the soil with 0.012 kg C/kg, its rate of cohesion recovery increased. Rate of cohesion recovery of this high organic matter soil was also increased by aging it at 0.1 kg $H_2O$/kg soil compared to 0.2 kg/kg. A possible explanation is that organic coatings, tending to prevent direct contact and bonding of adjacent projections of mineral surfaces, are forced away from contact points by extremely strong forces that pull the adjacent minerals together when soil water tensions are high. When the higher organic matter soil had been consolidated by air-drying and rehydrated, its rate of cohesion recovery was just as rapid as that of the soil with low organic matter.

*Additional Index Words:* diffusion, mineral bonding, interparticle contact, water tension.

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SOIL STRUCTURE IS DISRUPTED and bonds holding particles together are broken frequently as soil is frozen at high water contents, wetted quickly, tilled, or compacted (e.g., Bullock et al., 1987). As soils dry, increasing tension or negative pressure in the water (Briggs, 1950) pulls particles together, increasing the number of contact points at which bonding can take place in newly disrupted soils. Strengths of aggregates formed from disrupted soils increase with time (Blake and Gilman, 1970; Utomo and Dexter, 1981; Kemper and Rosenau, 1984), even when water content remains constant, indicating increasing strength of particle-to-particle bonds. "Soil structure" is dynamic in terms of both its geometric and cohesion characteristics.

The ultimate nature of the particle-to-particle bonds is atomic and ionic interactions. However, observations under optical microscopes (50–400 magnification) have shown us that as recently disturbed sandy soil dries, the retreating menisci pull small suspended mineral particles toward the points of contact between sand grains, forming additional contacts that bond the sand grains together. Methods for estimating strengths of sandy materials bonded by clays have been proposed by Ingles (1962) and Mullins and Panayiotopoulos (1984). These observations and the general positive correlation between clay content and aggregate stability in arid and semiarid soils (Kemper and Koch, 1966) indicate that clay plays a major role in the cohesion of larger particles. The following study was designed to further establish and define the role of clay and related factors in cohesion.

## PROCEDURE

Percentages of sand, silt, and clay; organic C content; and pH values are given, with locations of origin of the soils used in this study, in Table 1. Mineralogic descriptions of the clays in these soils indicate that illite is the dominant

type of clay in all three of them with smaller amounts of smectite, vermiculite, and kaolinite also present.

These soils were dispersed sonically, and three portions of the sediment containing primarily sand, silt, and clay, respectively, were separated by sedimentation. Particle size distribution in these portions was determined by the hydrometer method (Gee and Bauder, 1986), and the mineral portions were air-dried after allowing them to settle for 7 d, and decanting the supernatant liquid. Using the measured particle size distributions in the dominantly sand, silt, and clay portions of the soil, the amounts of each portion required to provide 100 g each of soil materials containing 5, 10, 15, 20, 25, 30, 35, and 40% clay was calculated. Ratios of silt/sand were kept within 10% of their values in the original soil sample. The dried materials were then crushed, mixed in the calculated portions, and 100 g of soil was wetted with 20 g of water. This wetted soil was then forced through a 2-mm sieve forming extruded "aggregates." These aggregates were stable while there was still tension in the water holding the particles together. However, if they were immediately immersed in water, which relieved that tension, the aggregates disintegrated.

Aggregates of each soil containing 5, 15, 25, 35, and 40% clay were stored in separate sealable jars. Two 3.6-g samples were taken immediately from each jar and exposed to an air stream carrying water vapor until they contained a total of 0.9 g of water per sample of aggregates. Their wet stabilities were then determined by placing them in sieves with 0.26-mm openings, immersing the aggregates in distilled water, oscillating the screens up and down for 3 min, and determining the portion of the particles <0.26 mm in diameter, which remained in aggregates >0.26 mm in diameter. (Oscillations were sinusoidal with amplitude of 13 mm and a frequency of 35 oscillations/min. See Kemper and Rosenau, 1986, for further procedural details.) Time from extrusion to wet sieving was about 20 min. Other sets of duplicate samples were taken from the sealed jars and wet sieved after they had aged for 4 h, 1 d, 5 d, and 30 d following extrusion. While aging, the sealed glass jars were stored in a dark cabinet at about 22°C. Water contents of aggregates remaining in the sealed jars after 30 d were the same as those 20 min after extrusion.

Moduli of rupture (MR) were determined on cores of soil 2.5 cm in diameter and about 5 cm long by laying the cores between two flat boards and increasing the force pushing those boards together until the cores ruptured (Kirkham et al., 1959). The cores were formed by pouring the extruded aggregates into brass cylinders containing an Al foil inner liner and compacting when the cylinders were about 1/4, ½, 3/4, and 4/4 full with a force of 80 kPa.

After packing, the inner liner and soil core were pulled out of the brass cylinder and the foil was peeled off the soil core. Moduli of rupture were determined on duplicate cores made of materials from each soil 4 min after packing for samples with clay contents of 5, 15, 25, 35, and 40%. Moduli of rupture were also determined on duplicate cores of each soil, with clay contents of 10, 20, and 30%, after being stored in sealed jars for 5 d, and 30 d after packing.

Table 1. Original particle size distributions, C content, pH values, and location of the soils used.

| Soil† | Sand | Silt | Clay | Carbon | pH | Sample location |
|---|---|---|---|---|---|---|
| | | % | | g/kg | | |
| Billings clay | 15 | 31 | 54 | 6 | 8.0 | Grand Junction, Co |
| Portneuf silt loam | 20 | 57 | 23 | 4 | 7.9 | Twin Falls, ID |
| Walla Walla silt loam | 24 | 54 | 21 | 12 | 5.6 | Pendleton, OR |

† Billings clay is a fine-silty Typic Torrifluvent; Portneuf silt loam is a coarse-silty, mixed, mesic Durixerollic Calciorthid; Walla Walla silt loam is a coarse-silty, mixed, mesic Typic Haploxeroll.

## RESULTS, DISCUSSION, AND SUPPLEMENTARY OBSERVATIONS

Moduli of rupture (MR) of cores made of separates from each of the three soils containing 0.2 kg $H_2O$/kg soil are shown in Fig. 1. In each soil the MR increased as clay content increased. Higher clay contents provide more opportunities for interparticle contact and also adsorb more water, causing higher tensions in soil water at a specific water content (0.2 kg/kg in this study). The MR also increased with time, indicating that in these moist soils, interparticle bonds strengthen with time.

Increased strength due to a constituent such as clay helps aggregates resist breakdown when they are subjected to shearing forces by tillage, freezing, fast wetting, compaction, etc. Consequently, the strengthening constituent helps maintain a more open structure with fewer particle-to-particle contacts than would have developed if the structure had disintegrated and the soil particles had been pulled into denser packing by forces due to gravity and water tension (e.g., Kemper et al., 1975). As Dowdy and Larsen (1971) pointed out, strength of the soil is limited by the number and strength of bonds between the aggregates. Consequently, the strength of soils, as measured on cores in this study or on other macroscopic soil units such as crusts, is highly dependent on previous disruptions and time and water content following disruption. These confounding factors often result in poor or negative correlations between strength (modulus of rupture, penetrability, etc.) measured on macroscopic soil units
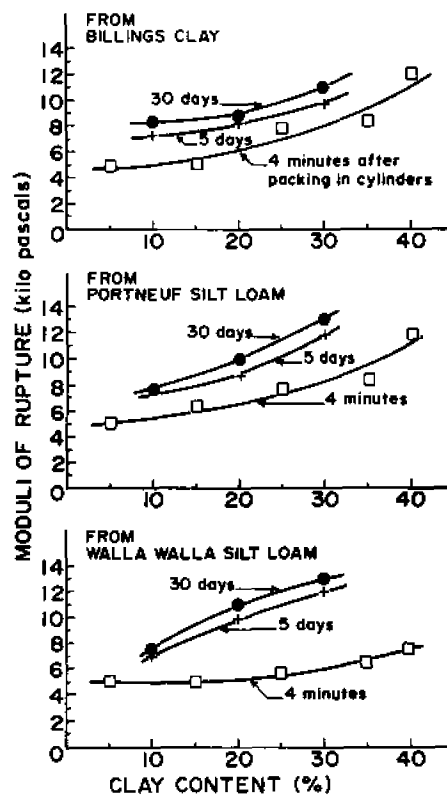


Fig. 1. Effects of clay content and time on moduli of rupture of cores of soil formed from particle size separates from the indicated soils, which were mixed, extruded into aggregates, packed into cores, and broken at 0.2 kg $H_2O$/kg.
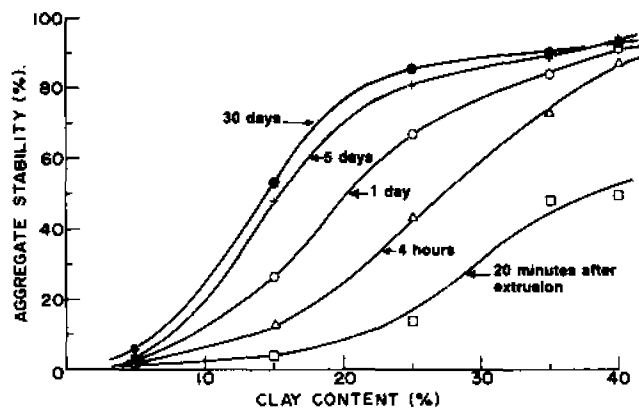
Fig. 2. Effects of clay content and time on stability of aggregates made of materials extracted from Billings soil, which were extruded and stored at 0.20 kg H₂O/kg.
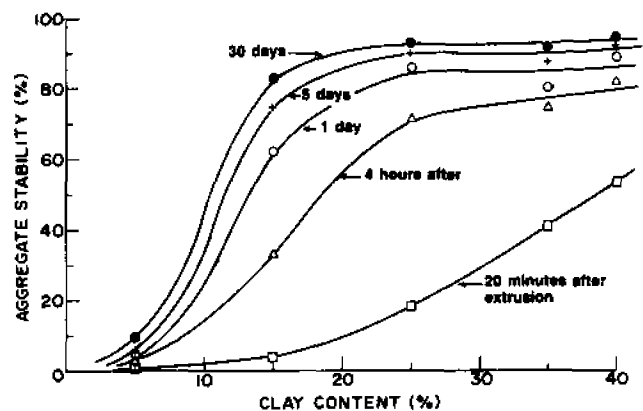


Fig. 3. Effects of clay content and time on stability of aggregates made of materials extracted from Portneuf soil, which were extruded and stored at 0.20 kg H₂O/kg.

and soil constituents such as clay, which strengthen bonding between larger particles.

These effects of prior sequences of disruption, wetting and drying on how clay affects strength of macroscopic units of soil are practically significant. A sequence of events that causes clay to be inactive as a bonding agent immediately following disruption, during consolidation of a soil mass, and to become active again as the soil ages or dries will result in the soil achieving high moduli of rupture. For instance, during flooding the soil surface is wet quickly and emergence of entrapped air disrupts interparticle bonds that were binding the microaggregates ($<250$ $\mu$m) together in aggregates. Substantial amounts of the clay are dispersed in the water and are relatively inactive as bonding agents while the microaggregates and larger soil particles are being pulled into dense packing by increasing tension in the water as the soil dries. During this drying, dispersed clay is pulled toward the contact points between larger soil particles or microaggregates. These clay particles often continue to move until they lodge between larger particles and form additional contacts between the large units. As drying continues the solution phase contracts to the immediate vicinity of the contacts and solutes are precipitated around those contact points, strengthening the cohesion. The result is hard surface soils, commonly called crusts.

Wet stability of extruded aggregates made from Billings soil materials increased with both clay content and time (Fig. 2). Previous studies (Kemper et al., 1985) have shown that unless their initial water content is at least 0.3 kg/kg, displacement of air when they are immersed contributes to breakdown of aggregates. Vapor moistening of the aggregates to that water content required about 20 min, therefore the first stability measurements were not taken until 20 min after the aggregates were formed. It is not possible to determine from these data which portions of the appreciable stabilities measured at 20 min at the higher clay contents are due to initial bonding by the colloidal particles, and which portions are due to the growing bond strength that developed during the first 20 min. Increase in aggregate stability and associated bond strength, at times, $>20$ min is probably due, at least

in part, to diffusion of molecular and ionic components to low energy positions where they bond between soil particles (Kemper and Rosenau, 1984).

The aggregate stability measurements are more sensitive to effects of the clay content and time than the moduli of rupture measurements. However, aggregate stability measurements provide only relative measures of the strength of cohesion and not absolute measure of that strength. This type of measurement has limitations. For instance, Fig. 2 indicates that stability of aggregates with 40% clay increased rapidly during the first 24 h following extrusion and then did not increase appreciably during the following 29 d. The bonds between particles in the 40% clay aggregates probably continued to strengthen during the following 29 d, as they did in the lower clay content aggregates. However, the strength of the cohesion in the 40% clay aggregates was sufficient after only 1 d of aging to withstand appreciable disintegration under the mild stresses applied by the hydraulic shear in this short-term sieving procedure. Extended sieving time (i.e., Fig. 10) or other procedures providing stronger disintegration forces, such as rapid wetting of dry aggregates, would have resulted in stability percentages appreciably lower than 100 at the end of 24 h and would have enabled monitoring of increased stability of the 40% clay aggregates after the first day.

At clay contents of 15 and 25%, stability increased appreciably faster in the Portneuf (Fig. 3) materials than in the Billings (Fig. 2). However, the Billings and Portneuf aggregates appear to be closely related when compared to the Walla Walla aggregates (Fig. 4), where rate of cohesion recovery was $<1$% as fast.

Failure of mineral particles to make contact often precludes possibilities of bonding between them. Water, strongly adsorbed on O surfaces of minerals by H bonding or held near the surfaces by osmotic forces associated with diffuse layer cations, tends to keep mineral particles from making direct contact with each other. As soil becomes drier, greater tension develops in the water phase. This general tension, acting on relatively large portions of the particle surfaces to pull them together, is often opposed primarily by pressures that develop in relatively small areas where the surfaces are within a few molecular layers of contact.
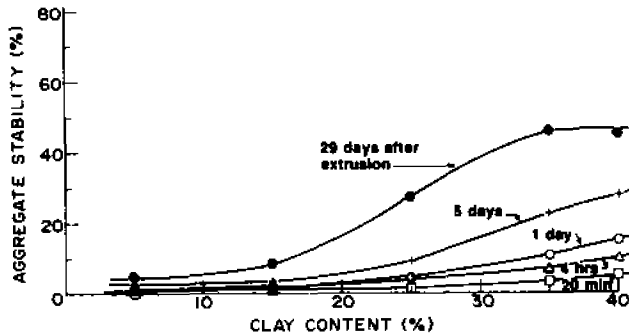
Fig. 4. Effects of clay content and time on stability of aggregates made of materials extracted from Walla Walla soil, which were extruded and stored at 0.2 kg $H_2O$/kg.



Fig. 5. Effects of clay content and time on stability of aggregates made of materials extracted from Walla Walla soil, which were extruded at 0.2 kg $H_2O$/kg, and stored at 0.1 kg $H_2O$/kg.

As the general water tension increases, the pressure on water between the particles in these small, near-contact areas increases until the pressure energy exceeds the energy with which water is adsorbed to the mineral surfaces. At this point water molecules are forced out of these areas and the mineral surfaces make contact.

In the small areas of contact various types of bonding between molecules take place depending on the atoms on the respective surfaces. Fusion, or partial integration of the crystal lattices of the two mineral particles, is possible over small contact areas with some minerals. Low energy positions develop around the circumference of those areas where a broad spectrum of ions, molecules, and amorphous gels (e.g., Uehara and Jones, 1976) can reside and help bind the particles together. Once these contacts are established, the strength of the resulting bond becomes a function of the rate of diffusion of molecules and ions to the low energy positions where they can attach to both mineral particles. Diffusion is slow when soil water content is low (i.e., Porter et al., 1960). Consequently, maximum rates of strength recovery occur when the soil is at intermediate water contents (Mitchell, 1960; Utomo and Dexter, 1981), where tension in the water is sufficient to pull particles into contact and there is still sufficient water for ions and molecules to move to low energy bonding positions.

To evaluate whether the slow cohesion recovery of Walla Walla soil could be increased by increasing the soil water tension and number of contact points, aggregates from the crushed Walla Walla soil formed by mixing and extruding at 0.2 kg $H_2O$/kg soil were dried to and aged at 0.1 kg/kg. After 4 h, 1 d, and 5 d of storage, samples of these aggregates were vapor wetted to a total of 0.3 kg $H_2O$/kg of soil, immersed, and wet stability was determined. Aging the aggregates at 0.1 kg $H_2O$/kg of soil rather than 0.2 kg/kg increased the tension in the water from about 80 kPa to > 1600 kPa, while reducing the area over which the tension is exerted by a factor of about 2. The net effect increases pressure on near contact points by a factor of about 10. This higher tension during the aging period resulted in substantially higher stabilities (Fig. 5 compared to Fig. 4). These increased stabilities were probably due primarily to more particle-to-particle contacts. The relatively rapid increase in stability from 4 h to 5 d after extrusion was probably due primarily to strengthening of those bonds since soil-water content
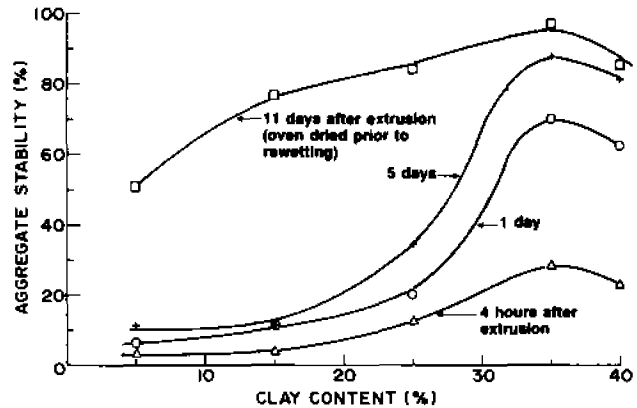
remained constant. This increase in stability was particularly large in the high clay content mixtures (Fig. 5).

Bonding of sand grains and glass spheres has been observed (e.g., Gifford and Thran, 1976) as water evaporates from the porous matrices and the slightly soluble solutes are pushed toward the particle-to-particle points by the retreating air-water interfaces.

Such possible bonding mechanisms associated with the drying process indicated the need to see what drying would do to this soil. Consequently, after 11 d of aging at 0.10 kg $H_2O$/kg of aggregates, the Walla Walla aggregates were oven dried for 2 h. The aggregates were exposed to an air stream bearing water vapor until they had adsorbed 0.3 kg $H_2O$/kg aggregates. Then the aggregates were immersed in water. When clay contents of the aggregates were <30%, drying greatly increased their wet sieve stabilities (upper curve of Fig. 5). Since Fig. 2, 3, and 4 indicate only small increases in aggregate stability due to aging from the fifth to the eleventh day after extrusion, most of the increase in stability and strength of bonding was due to factors and processes associated with drying.

To further evaluate the effects of drying on rate of cohesion recovery, samples of Walla Walla, Portneuf, and Billings soils were disrupted by moistening to 0.2 kg $H_2O$/kg and then crushing and extruding them through a 2-mm sieve. Half of each treatment was kept at 0.2 kg $H_2O$/kg soil for the times indicated in Fig. 6. The other half was air-dried under a fan for 2 h, remoistened to 0.2 kg $H_2O$/kg, and aged for the times indicated. All samples were then moistened to 0.3 kg $H_2O$/kg by exposing them to a stream of vapor laden air, and aggregate stabilities were determined.

Air-drying prior to rewetting and aging caused significant but relatively small increases in aggregate stability in the Portneuf and Billings soils. In the Walla Walla soil, air-drying overcame the factor that was keeping this soil from regaining its cohesion. Particles pulled into contact by the drying process apparently remained in contact when the soil was rewetted slowly by vapor and strength of the bonds continued to grow. These findings show that drying overcomes the factor that was preventing Walla Walla soil from regaining its cohesion, but it does not define that factor.
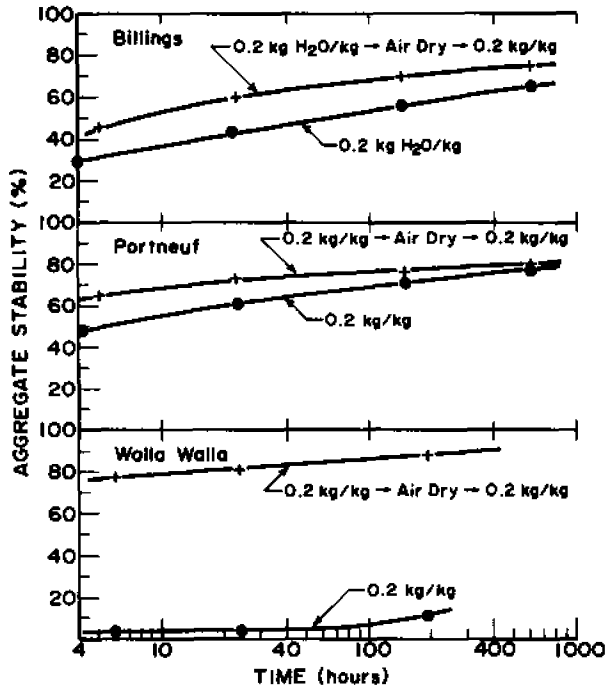
The Walla Walla soil is from an area of higher rain-

Fig. 6. Effect of air-drying and vapor rewetting on cohesion of recently disrupted soils.



Fig. 7. Cohesion recovery of Walla Walla soil as affected by organic matter and water content following disruption.

fall so its organic matter content is appreciably higher. Thus, a larger portion of the mineral surfaces are coated by organic compounds that may reduce the number of mineral-to-mineral contacts where inorganic ions and/or molecules can bond adjacent mineral surfaces together. The mechanism involved here could be similar to the manner in which a thin layer of oil between a metal bolt and a threaded hole will help keep the metal surfaces from seizing or bonding together.

To evaluate whether organic matter in the aggregates could be having this negative effect on recovery of cohesion, organic matter was removed from a sample of the Walla Walla soil as follows. The whole sample was saturated and dispersed by ultrasonic vibrations. Half of the sample was then treated with hydrogen peroxide to remove the organic matter by oxidation in a manner similar to that in Treatment II used by Lavkulich and Wiens (1970). However, following the second $H_2O_2$ addition the slurry was again sonified to help open the internal surfaces to the oxidation reaction, and following the final $H_2O_2$ addition the 100-g soil sample was allowed to settle overnight, the supernatant solution was drawn off, the sample was mixed with 1 L of 0.005 $M$ $CaCl_2$, the soil was allowed to settle, and the supernatant solution was removed again. Both the oxidized treatment and the unoxidized treatment (which had been treated the same except for the $H_2O_2$ additions) were then dried to 0.20 kg $H_2O$/kg soil and extruded through a 2-mm sieve. Half of each treatment was kept at this water content and the remainder was dried to 0.10 $H_2O$/kg soil and stored in sealed containers. Stabilities of aggregates from each of the four treatments were determined after 3.5, 24, and about 156 h and are graphed in Fig. 7.

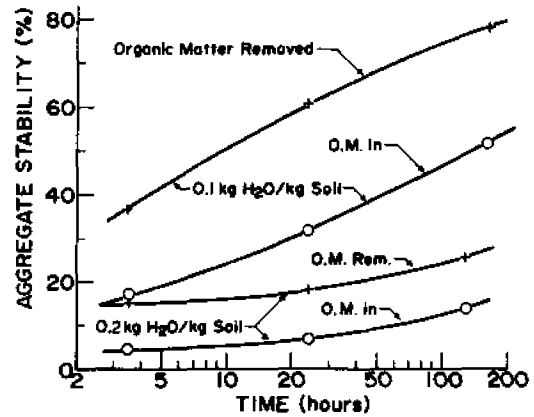The $H_2O_2$ treatment resulted in cohesion recovery >10 times as fast as when the organic matter was

present in the soil, when the soil was aged at both 0.10 and 0.20 kg $H_2O$/kg soil. This appears to support the suggestion that the higher organic matter content of the Walla Walla soil was a primary factor in its cohesion recovery rate being slower than those of the Portneuf and Billings soil. However, as shown by Lavkulich and Wiens (1970), $H_2O_2$ oxidation and washing of this type also removes substantial amounts of extractable Si and Al, which were associated with organic matter in the soil. Removal of these components may also have played a role in the more rapid recovery of the oxidized soil. Hydrogen peroxide treatment to remove organ matter from the Billings and Portneuf soils caused smaller, but significant, increases in their rates of cohesion recovery. However, at 0.2 kg $H_2O$/kg soil, rate of cohesion recovery of the $H_2O_2$-treated Walla Walla soil was still lower than that of the Billings and Portneuf, indicating that factors in addition to those removed by $H_2O_2$ retard cohesion recovery in the Walla Walla soil.

In an effort to determine whether microorganisms were involved in the observed cohesion recovery, recently disintegrated and extruded aggregates were autoclaved at about 100°C to kill the microorganisms. Instead of decreasing the rate of cohesion recovery as a result of killing the microorganisms, autoclaving increased cohesion recovery.

Rates of biological reactions increase as temperatures increase above 0°C, usually reaching a peak in the 30 to 40°C range and decreasing rapidly to zero at higher temperatures. Rates of physical-chemical reactions involving diffusion in water increase as temperature increases up to the boiling point of water, at which diffusivities of ions are about six times those at 0°C. To help identify the types of reactions responsible for cohesion recovery, extruded aggregates made of Portneuf soil were incubated at 0, 23, 60, and 90°C for 216 h. At the times indicated in Fig. 8, aggregate stabilities were determined. Rates of stability recovery continued to increase up to 90°C indicating that the processes involved are primarily physical-chemical in nature. However, the increases in cohesion recovery rate as temperature increases are even greater than those that would be predicted if diffusion was the only limiting factor. It is probable that factors, such as increased solubilities or reactivities at higher tempera-
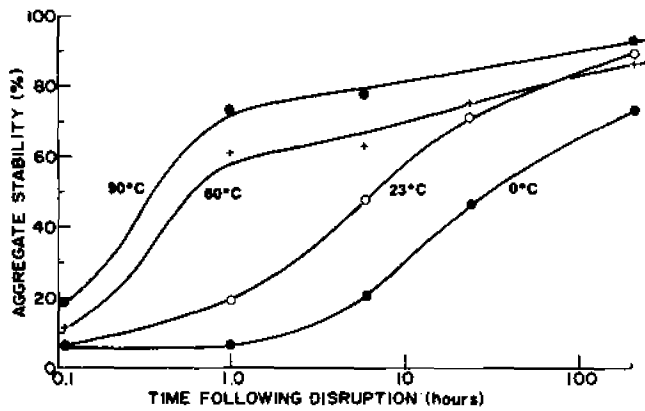
Fig. 8. Effect of temperature on rate of cohesion recovery of a disrupted Portneuf soil.
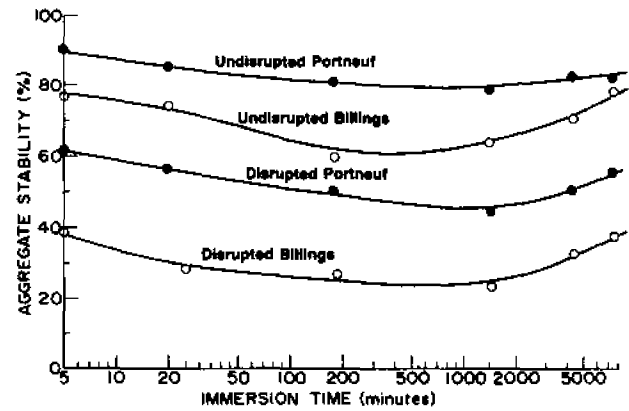


Fig. 9. Effects of immersion time on stabilities of aggregates formed and quickly dried from disrupted soil and of natural aggregates from Billings and Portneuf soils.

tures of some of the compounds involved, further accelerate rates of cohesion recovery.

The pH of unfertilized Walla Walla soil is commonly around 6.6, but in this soil the pH was down to 5.6 as a result of 50 yr of fertilization with 90 kg/(ha crop) of $NH_4$-$NO_3$. The Billings and Portneuf soils had pH values near 8. Electrical charges associated with edges of clay particles are pH dependent. Oxygen atoms on the edge of the clay lattice often have unsatisfied negative charges. When the pH is low, these negative charges are largely paired with the abundant hydrogen ions resulting in uncharged —OH pairs on the edge. When the pH is high, and the exchange capacity is filled largely with Ca ions, most of the unsatisfied O on the crystal edges are paired with divalent Ca ions resulting in positively charged —OCa$^+$ on the edges. Hydrogen bonding can occur through —OH pairs to the O which comprise most of the surface of clay minerals. The strength of such bonds is small, however, compared to the electrostatic bonding of — OCa$^+$ to the negative charges in the clay lattice that are due to isomorphous substitution. Consequently, there are greater opportunities for stronger edge-to-surface bonding of clay particles in high pH than in low pH soils. These possibilities in high pH soils for stronger edge-to-face bonding of clay particles might be a factor causing initial cohesion between clay particles, which could help keep these particles in close proximity while other molecules and ions occupy and diffuse to low energy bonding positions.

To evaluate this factor, Kemper et al.[3] added powdered $CaCO_3$ and $Ca(OH)_2$ to samples of this Walla Walla soil and subjected them to several wetting, stirring, and drying sequences until their pH values were about 8.1. The rate of cohesion recovery, as measured by increasing stability of macroaggregates (>0.26 mm), was slower than in the original low Ca$^{2+}$ soil similarly wetted, stirred, and dried with a pH of 5.6. Smectite type clays, saturated with Ca ions, are bonded together with sufficient strength to resist dispersion when immersed in water (e.g., Norrish and Quirk, 1954). The divalent Ca ions apparently bond adjacent platelets of clay together by occupying positions between negative

charges that are nearest to each other in the adjacent platelets. This same type of bonding probably tends to occur between external planar surfaces of illite clays. The failure of Ca$^{2+}$ saturated systems to have higher aggregate stabilities may be rationalized by considering that the bonding of clay particles into thicker domains or tactoids makes them more blocky and rigid and less able to conform and laminate to adjacent rigid surfaces. However, this leaves the explanation of the more rapid recovery of cohesion in the Portneuf and Billings soils as primarily due to their lower organic matter contents.

To help evaluate the nature of the bonding that occurs as drying takes place, Portneuf and Billings soils were sampled, air-dried, and aggregates in the size range from 1 to 2 mm were separated by sieving from one-half of each sample. The other half of each sample was wetted to 0.25 kg $H_2O$/kg soil, crushed, and extruded through a 2-mm sieve, which previous studies have shown destroys a major portion of the bonds that hold aggregates together and reduces the wet aggregate stability of these soils to near zero. These assemblages of microaggregates, held together by surface tension of the water, were then air-dried for about 20 h, which resulted in some rebonding. Then samples of aggregates from each treatment were vapor wetted to about 0.3 kg $H_2O$/kg soil, immersed, and sieved for 5 min. Stabilities of these aggregates are shown on the left side of Fig. 9.

At the same time, 10, 3-g samples of each treatment were placed on sieves and immersed in water at 23°C. After 20, 180, 1400, 4300, and 7500 min of immersion, duplicate samples were taken from each treatment and sieved according to the standard procedure. Stable aggregates remaining on sieves at ends of those immersion times (immersion time is equal to soaking plus sieving time) are shown in Fig. 9. Although the disrupted and reformed aggregates had bonded together and regained appreciable stability during the 20-h drying process, they were still much less stable than the natural aggregates. The slow decline in stability of both the natural and the disrupted and quickly rebonded aggregates during the first 1400 min was probably due to solubilization of slightly soluble compounds that were helping cement the components together in the aggregates. During the time period from

[3] W.D. Kemper, C. Douglas, and C.R. Rohde. Soil cohesion and its recovery as affected by long term residue management. Soil Sci. Soc. Am. J. (manuscript to be submitted in 1987).
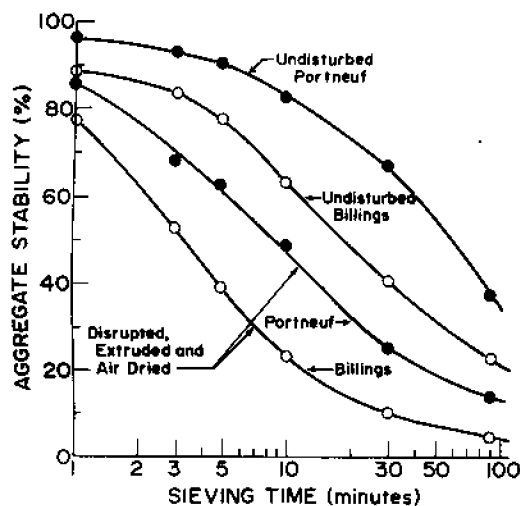
Fig. 10. Effects of sieving time on natural aggregates and on aggregates from disrupted and quickly dried soil.

1400 to 7200 min (1–5 d), the stability of the aggregates tended to increase. This may have been due to component ions, atoms, and molecules migrating to lower energy positions where they are more effective in bonding particles together. Such increases are common in strength of porous materials, such as freshly precipitated crystals, concrete, etc., when they are kept moist so atomic size components can diffuse from positions of high to positions of low energy via the liquid phase. These increases in cohesion with time during soaking for >1 d in saturated systems are also similar to those shown in Fig. 1 to 4 for soils at 0.2 kg $H_2O/$ kg soil.

To further compare the strength of the bonds in the disrupted soils formed by quick drying to those in normal soils, portions of the Portneuf and Billing soils prepared as described for Fig. 9 were sieved for times ranging from 1 to 90 min. The resulting aggregate stabilities are indicated in Fig. 10. It appeared that practically all of the aggregates left on top of the screen after 1 min of sieving were >0.26 mm and that smaller particles and microaggregates had found their way through the sieve. Extrapolation of the lines in Fig. 10 to a sieving time of 0.1 min indicates that the slow vapor wetting prior to immersion practically eliminated the disruptive forces associated with quick wetting, leaving all of the sample in the range of +90% aggregate stability immediately after immersion. Therefore, the factors reducing the stability are primarily the shear forces of the water coupled with the abrasive forces associated with other aggregates in the sieve. The initial rates of disintegration were five or six times as great for the aggregates formed from quickly dried disrupted soils as compared to rates of disintegration of undisrupted aggregates.

## CONCLUSIONS

In the range of clay contents from 0 to 35%, higher clay contents resulted in development of greater stability of aggregates formed from these disrupted soils. When water contents were 0.2 kg/kg, stability of aggregates made from these disrupted soils all increased with time. The rate of increase was >100 times faster

for aggregates from the Portneuf and Billings soils (pH about 8, organic C about 4 and 6g/kg, respectively) than for aggregates from the Walla Walla soil (pH about 5.6 and organic C about 12g/kg. Possible reasons for this difference include better mineral-to-mineral contact facilitating fusion type mineral bonding in the low organic matter soils. Higher rates of cohesion recovery in soils with lower organic matter and in soil from which organic matter was removed indicate that organic matter may hinder recovery of cohesion. Increasing rates of cohesion recovery as temperature increases up to 90°C show that microbial reactions are not a primary factor in the observed cohesion recovery and that it is primarily physical-chemical in nature.

Drying samples quickly to equilibrium with relative humidities <75% causes substantial bonding in disrupted soils with clay contents from 5 to 40%. This bonding appears to be due to combined deposition of colloids and precipitation of slightly soluble minerals around the contacts between the larger particles as the air-water interface retreats to those contact points. Since the bonds formed are stable, even after the aggregates are immersed for several days, the bonding process involves irreversible or slowly reversible reactions. Increases with time of interparticle bond strength, when water tension is in the 100 to 1500-kPa range and water content is constant, are probably due to bonding between adjacent particles by ions, molecules, and possibly small collodial particles that have diffused from higher energy positions in the solution or solid phase to these lower energy binding positions.

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