Verification of the structural model of clay-water system

Vérification du modèle structurel du système argile-eau

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SYNOPSIS: Scanning /SEM/ and transmission /TEM/ electron microscope evidence is presented of the parallel arrangement of smectite particles in domains, their possible delamination and collapse, their gradual aggregation and plane- parallel fissure formation between structural elements. Thus some postulates of the long-range interaction theory /DLVO/ and those of the structural model are proved to be correct. Suggestions of the deformation mechanism of the clay-water system are given.

Basing on semi-theoretical, semi-empirical considerations, a structural model of smectitic clay-water system was developed, which explains clay behaviour in mechanical processes and which may be used for its prognosis /Stępkowska, 1988/. This model according to Lambe's definition considers arrangement of clay particles /fabric/ and forces between them. Long-range forces for parallel particle arrangement may be calculated from DLVO-theory. A good agreement was obtained between the calculated and the measured values, e.g. between the calculated van der Waals attraction and the measured cohesion /Stępkowska, 1987, 1988/.

Main postulates of the structural model are:

/1/ stepwise aggregation of the structural elements and their regular distribution in space, i.e. parallel particles --> domains --> aggregates --> superaggregates --> macroaggregates /Figs. 1 to 6/,

/2/ plane-parallel fissure formation between structural elements due to repulsion between them which causes also $u_w < 0$ /osmotic pressure, p_R, see Figs. 6 to 11/,

/3/ thus the total water content is composed of /a/ crystal phase water, W_h, equal approximately to hygroscopic water content, measured at $p/p_o = 0.95$ and proportional to external specific surface of clay particles, /b/ diffuse layer water, W_d, contained between plane parallel faces of structural elements, separated by the distance $2\underline{d}$ /Figs. 6 to 11/ and /c/ interaggregate or macropore water, W_m /Fig. 5/. All these components may be determined experimentally.

/4/ DLVO-theory is valid for calculation of diffuse layer repulsion, p_R, and van der Waals attraction, p_A,

/5/ contact bonds may exist between structural elements but they may not be disturbed by moderate stresses /Figs. 1, 11, 14/,

/6/ particle thickness is uniform in the given system /Fig. 12/ but it is variable /Stępkowska, 1980, 1988/,

/7/ the system may separate into various microstructural phases /parallel, cluster, floc/ to fulfill the local equilibrium condition of external and internal pressures /Stępkowska and Jefferis, 1983/.

Here evidence is presented mainly in support of postulates /1/ and /2/. Remaining postulates were and will be discussed elsewhere. This paper is also limited to isotropic system.

This evidence was mainly found during the study of suspensions of two commercial bentonites /Berkbent and Brebent/ used in Civil Engineering. These bentonite-water suspensions were prepared at various concentrations /4% to 10%/, various stirring energies /2000, 5000 and 7000 RPM/ and various stirring times /5 and 15 min/. They were dried in glass cylinders, Ø = h = 5cm see Figs. 7 and 8, either at ca. 20°C /unstored/ or at 45°C after various storing times /here 2 or 3 months, series a, and 8 months, series f and g/. Drying rate was recorded. Dried specimens were tested by SEM, XRD, TG and water sorption was measured /Stępkowska and Jefferis, 1983/.

According to the structural model the compression process may be presented as a stepwise rigid-elasto-plastic deformation of the system of structural elements /Fig. 14/. It depends on the magnitude of the normal stress what size of the structural elements takes part in deformation due to shear stress. Contact bonds may contribute to the peak strength value, which is not shown in the Fig. 14.

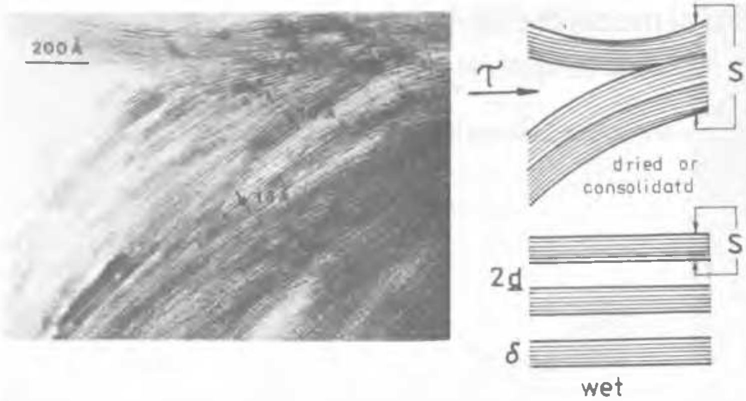
Equation for volume change in the consolidation process /proportional to change in water content/ may be derived as follows: water content

$$W = W_h + \sum_i W_{di} + \sum_i W_{mi}$$

total	crystal phase	diffuse layer	interaggregate
		on i-th aggregation level	

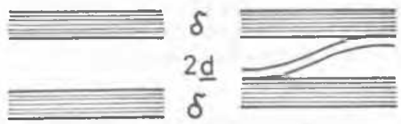
If multiplied by ρ_s/ρ_w these components represent volume contributions V_h, V_{di}, V_{mi} per unit volume $V_o = 1/\rho_s$ and $W_{di} = V_{di} \cdot \rho_w = \underline{d}\, S_i\, \rho_w$, where S_i is the specific surface of the given structural element.

Substituting the sum of V_{di} by $/\underline{d}\, S/$ and the sum of V_{mi} by V_m we obtain



Ahn and Peacor, 1986, TEM.

Figure 1. Parallel smectite particles of the thickness δ = 10 to 20 nm, forming a domain, which shows a possible delamination that may occur due to /a/ shear stress, τ, whereas normal stress, σ_n, causes collapse, /b/ excess pore water pressure, /c/ water vapour in water sorption from dry state. S is the external specific surface /variable/, 2$\underline{d}$ is the interparticle distance. Hygroscopic water, W_h, is sorbed on the external and internal surfaces, usually in three-molecular layer and it may be estimated as water sorbed at p/p_o = 0,95. There is the diffuse layer water, $W_d = \underline{d}\, S\, \rho_w$ between parallel particles and other structural elements. Parallel particle arrangement is due to long-range diffuse layer repulsion.



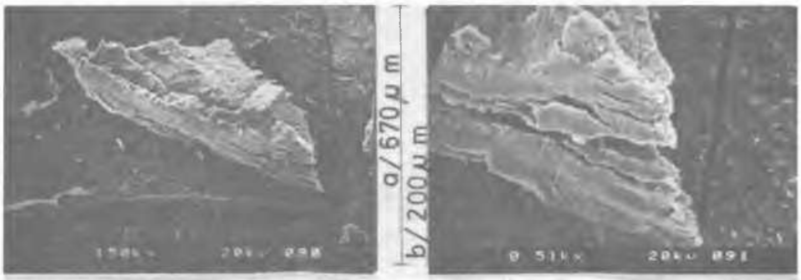


Figure 2. Illustration of "bridges" between particles or domains and of gradual delamination: grains partly formed of parallel structure on the surface of a superaggregate. B/R-1g, 4% Brebent, 2000 RPM, 5 min, stored 8 months, dried at 45°C.

Figure 3, A cluster in Brebent bentonite. In wet state this cluster assumes a more regular form /B/R-2, 5%, 2000 RPM 5 min, unstored, dried at 20°C/.

Figure 4. Aggregates formed of clusters: /a/ in unstored Berkbent bentonite /B/R-2, compare Fig. 3/ and /b/ in that stored for ca. 8 months /B/R-2g, dried at 45°C/.

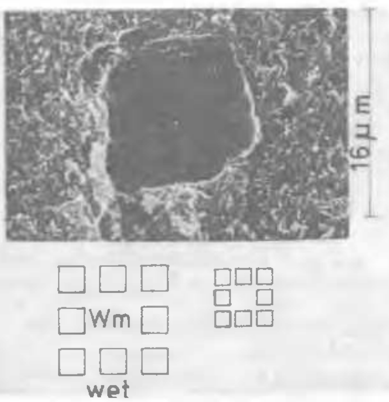


Figure 5. Vacancy in an "aggregate lattice" /B/B-A, 6%, 5000 RPM, stored 8 months, dried at 45°C/.

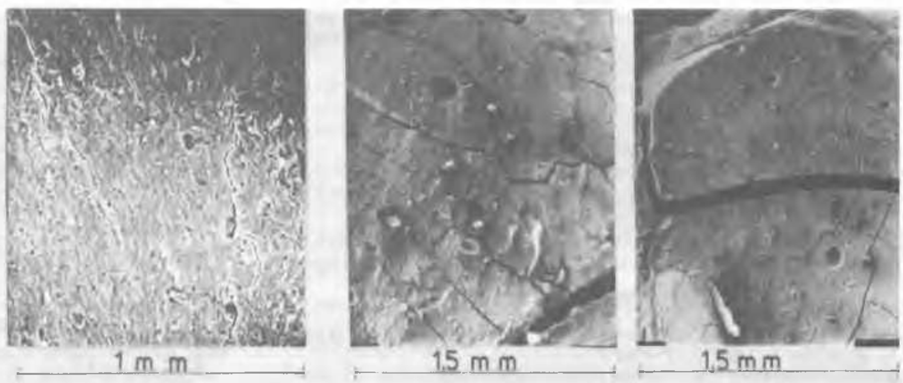


Figure 6. Formation of superaggregates /aggregates of aggregates/ in Berkbent bentonite suspension during storage: /a/ B/B-B, 6%, mixed by hand, unstored, dried at ca. 20°C, /b/ B/B-10f, 7% and /c/ B/B-12f-9%, both stirred at 5000 RPM, 15 min, stored 8 months dried at 45°C

B/B-9a, 6%   B/B-10a, 7%
stored for 3 or 2 months

B/B-9f, 6%   B/B-10f, 7%
stored for 8 months

Figure 7. Desintegration into equal parts of some Berkbent bentonite suspensions after 3 days of drying at 45°C. This indicates the presence of macroaggregates in suspension.

B/R-1 4%	B/R-1f	B/R-4 5%	B/R-4f	B/R-3a, 6%	B/B-9a, 6%
unstored	stored 8 month	unstored	stored 8 months		stored 2 or 3 months
2000 RPM, 5 min		7000 RPM, 5 min		2000 RPM,5min	5000RPM, 15 min

Figure 8. Dried residuals of Brebent /and Berkbent -9a/ bentonite. Note the desintegration of specimens B/R-1f and B/R-4f into three equal parts and B/R-3a into two equal parts, which indicates the presence of macroaggregates in stored suspensions before drying. Fissures between them may cause increased filtration. Specimen B/B-9a formed a regular cylinder. Note the numerous macropores inside the specimen B/R-1f.

B/B-A, 6%

Figure 9. Development of plane-parallel fissures between aggregates in Berkbent bentonite suspensions from irregular form in unstored one /a/ to regular form after 8 months storage /b/ and /c/. All specimens stirred at 5000 RPM for 15 min.

Figure 10. Plane-parallel fissures in dried Brebent bentonite suspension after 8 months storage before drying at 45°C /B/R-2g, 5%, 2000 RPM, 5 min/. These fissures may cause increased filtration in situ, e.g. in earth dams.

Figure 11. Possible formation of contact bonds between aggregates of Berkbent bentonite, stored for 8 months /B/B-10g, 7%, 5000 RPM, 15 min/

Figure 12. Uniformity of particle thickness after desintegration in microtome cutting /TEM, vermiculite, courtesy of H. Graf von Reichenbach/

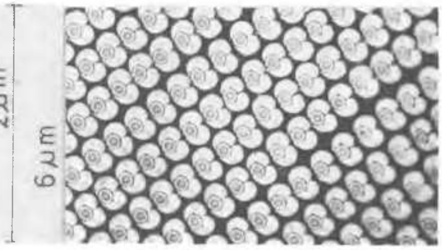


Figure 13. Regular arrangement of living cells /cross section/, TEM, Spermatozoa from the bug Laccotrephes spec./Courtesy of B.A.Afzelius,1987/

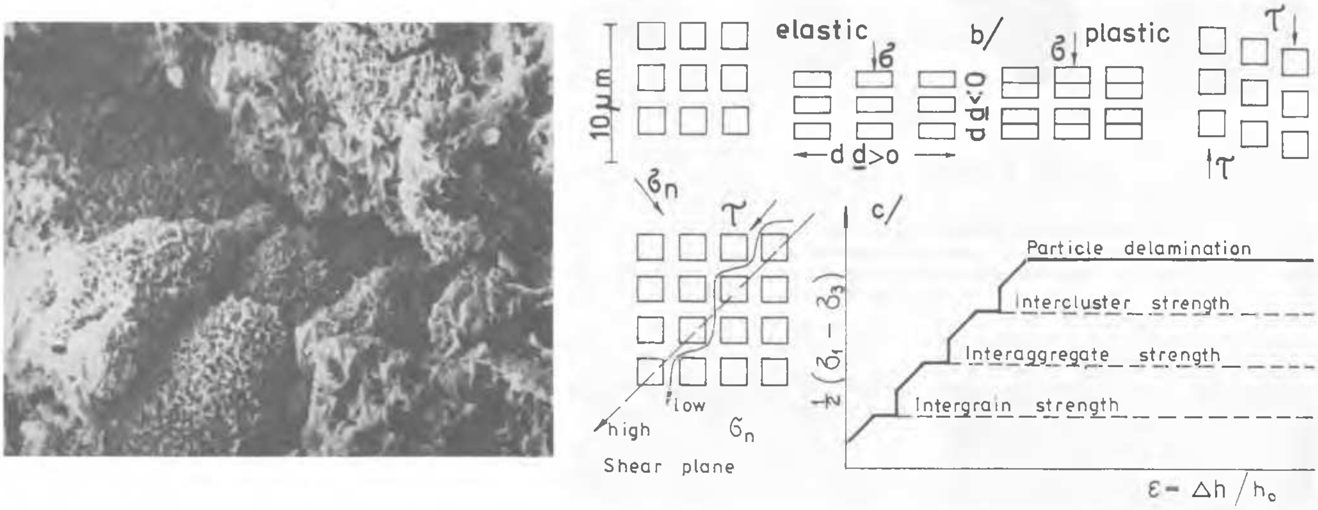


Figure 14. Deformation of an isotropic system in axial compression: bentonite from Zrecze Małe, compressedn axially /a/, deformation of the structure /b/, stress - strain curves /c/.

$$\frac{dV}{d\sigma} = \left[\frac{\partial v_h}{\partial \sigma} + s\left(\frac{\partial \underline{d}}{\partial \sigma}\right)_s + \underline{d}\left(\frac{\partial s}{\partial \sigma}\right)_{\underline{d}} + \left(\frac{\partial v_m}{\partial \sigma}\right)\right]_{u_w}$$

$$+ \left[\frac{\partial v_h}{\partial u_w} + s\left(\frac{\partial \underline{d}}{\partial u_w}\right)_s + \underline{d}\left(\frac{\partial s}{\partial u_w}\right)_{\underline{d}} + \left(\frac{\partial v_m}{\partial u_w}\right)\right]\frac{\partial u_w}{\partial \sigma}\Bigg|_{\sigma + d\sigma}$$

$$= -\left[C_s + C\,B\right]$$

This is comparable with equation written by Fredlund /1987/:

$$-\Delta V/V_o = C_s\,\Delta/\sigma - u_w/ + C\,\Delta u_w$$

where he defines C_s and C as compressibilities of soil structure and of soil particles respectively. Note that $\partial u_w/\partial\sigma$ is the Skempton parameter B. Further discussion is outside the scope of this paper.

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