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# Organo-Mineral Formations as a Form of Interaction Between Living and Inert Matter

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**Abstract:** The interaction of mineral components of the soil or mineral particles of aqueous suspensions with organic matter confirms the idea of V.I. Vernadsky about the constant exchange between non-living (inert) and living matter in the biosphere as the basis of life. Such interactions are most clearly manifested in the mixing zone of sea and river waters. Experiments conducted on models have shown that the combined action of humic substances adsorbed onto mineral particles (inert matter) and polyelectrolytes formed in situ (living matter) leads to more efficient flocculation in the presence of salt than flocculation of unmodified mineral particles. Various types of humic preparations were studied as clay modifiers. Sakhalin humate was shown to stabilize clay dispersions better than other humates, even at increasing salinity. The origin of polyelectrolytes acting as flocculants is considered. The results of the study confirm the important role of humic substances as an intermediate link from living to non-living matter, and the found quantitative ratios of humic acids and flocculants can be used in the remediation of soil structure, in water purification, in the study of mass transfer of river suspended matter and associated pollutants from river waters to the marine environment.

**Keywords:** aggregative stability; coagulation; flocculation; soil structure; bentonite; humic substances; chitosan; inert matter; living matter.

## 1. Introduction

V.I. Vernadsky's idea of the biosphere as an area of life in which the interaction of living matter and inert substances occurs is the foundation of many processes in nature and the basis of the life process. According to V.I. Vernadsky, living matter, as a collection of living organisms, is active, labile, and aimed at the reproduction of its own structure. Non-living substances, on the contrary, are inert, but have greater stability in comparison with living bodies and contribute to their survival [1-3]. Organo-mineral formations of soils serve as a classic example of such interaction [4-7]. The mineral components of the soil, due to their highly dispersed state, have high surface energy. This condition is thermodynamically unfavorable. A decrease in surface energy is possible during the adsorption of soil organic matter (OM) on the surface of mineral particles. Thus, mineral surfaces can influence the chemical composition of organic compounds, thereby conferring stability, and can also influence the composition of free OM [8].

Most OM in soils, both adsorbed and free, is represented by humic substances (HS) [9-12]. One of the debated issues is the question of what can be defined as HS and how they can be separated from other OM [13-16]. The definition proposed on the website of the International HS Society (IHSS) is: HS are complex and heterogeneous mixtures of polydisperse materials formed in soils, sediments, and natural waters as a result of biochemical and chemical reactions during the decomposition and transformation of plant and microbial residues [17]. HS are characterized by polydispersity, high molecular weight (MW) ranging from a few hundred to millions of daltons, and high biothermodynamic stability [18]. HS have a diphilic nature, being able to be adsorbed on both hydrophilic and hydrophobic surfaces [19-23]. During humification, nonliving OM undergoes transformation, forming the most stable compounds, with no analogues in living organisms. According to [24], HS are considered as dynamic, non-polymeric complexes of individual molecules that combine into supramolecular aggregates stabilized by weak interactions (such as van der Waals forces, hydrophobic interactions, and hydrogen bonding).

Recent studies have revealed that the key mechanism of OM transformation is the oxidative dearomatization of polyphenolic molecules, leading to an increase in the number of oxygen-saturated aliphatic structures [25]. Traditionally, HS are classified into three fractions based on their solubility characteristics: humic acids (HA), fulvic acids (FA), and humin [16]. In the time scale, biochemical and chemical degradation during the humification can be followed by biogeochemical transformation when OM is replaced by mineral compounds. The fossilization of plant remains may serve as an indicator of lithogenesis [26].

The question of how HS can be considered as inert substances is rather ambiguous. The difficulty is that OM extracted by conventional methods contains both highly transformed OM and products of soil biota. In this context, the mineral matrix is considered an inert substance, whereas OM forming in situ is regarded as living matter, and HS acts as a bridge between them.

There are different factors that affect the interaction of natural OM and mineral compounds. One of them is mineral structure. In this work, we investigated bentonite clay, which has unique properties and, having a high adsorption capacity (due to its ability as a three-layer silicate to swell), can serve as a matrix for the sorption of OM. Our approach is based on the study of the mechanism that exists in the mixing zone (where river water mixes with sea water), leading to the sedimentation of river suspensions and the formation of deltas, the soils of which are characterized by high fertility. Thus, both phenomena, the sedimentation of river suspensions in mixing zones and the formation of soils, are based on the same mechanism. The idea is that HS adsorbed onto soil or suspended mineral particles interacts with polyelectrolytes (PE) formed in situ by living matter, giving organo-mineral polymer aggregates. The formation of such aggregates was studied using a model system: bentonite (in suspension and paste) modified with HA (an inert substance) and chitosan, a natural polysaccharide widely used in flocculation (living matter). The aim of this work is to study the interaction between mineral components of river suspensions and OM, as an interaction between living and inert matter (according to V.I. Vernadsky), and to evaluate the various factors influencing this process.

## 2. Materials and Methods

### *2.1. Materials.*

#### 2.1.1. Model of inert substance.

Bentonite (Oglanli deposit, fraction <1 μm >50%). Themineral composition of betonite is: $SiO_2$ – 68.61; $Al_20_3$ – 12.71; $Fe_2O_3$ – 1,13; FeO – 0,14; $TiO_2$ – 0.17; CaO – 1.58; MgO – 2.39; MnO – 0.03; $Na_2O$ – 0,94; $K_2O$ – 0,24; $P_2O_5$ – 0,06; $H_2O$ – 4.83; not defined – 5.89; Σ – 98.72 [27].

#### 2.1.2. Humic substances.

Potassium humate (HA-Pow) isolated from brown coal - leonardite (Powhumus, Germany); Potassium humate under the trade name Sakhalinsky humate (SH) isolated from leonardite using alkaline isolation from oxidized lignite (Sakhalinsky Humates, Russia); Potassium humate under the trade name Lignohumate (LH) was produced by thermal oxidative hydrolytic treatment of technical lignosulfonates under high pressure (Realization of Ecological Technologies, Russia), MWs 60 ÷ 75 kDa. All substances were commercial preparations obtained according to a standard IHSS procedure, and they were used as received [17]. The pH of 1% aqueous solutions of the studied HA acids was: 6.86 (±0.05, n=5), 7.70 (±0.19, n=5), and 7.12 (±0.29, n=5) for HA-Pow, SH, and LH, respectively.

#### 2.1.3. A model of living matter.

Chitosan (Ch) – natural polyelectrolyte, MW 83 kD, degree of deacetylation 92%, in acetate form (Bioprogress, Russia), widely used as a flocculant. The Ch solution (0.5 g/L) was prepared in 1% $CH_3COOH$. Chemically pure NaCl was used without purification to model water samples in the river-sea zone.

### *2.2. Methods.*

#### 2.2.1. Preparation of clay suspensions.

2 g of clay was added to 1 liter of distilled water at room temperature (RT), stirred mechanically for 20 minutes, and left to swell for at least 5 days, shaking it periodically by hand.

#### 2.2.2. Preparation of colloidal bentonite.

Colloidal bentonite (0.3 g/L) was prepared by decanting the bentonite suspension after settling of coarse particles for 10 days at RT. The particle size was 180-200 nm, and the zeta potential was -37 mV.

#### 2.2.3. Preparation of clay pastes.

5.0 g of bentonite powder was soaked in 10 mL of distilled water and stirred by hand for 15 minutes to form a thick paste. Then 10 mL of water was added, and stirring was continued for 15 minutes. The paste was then left for 24 hours at RT, after which the remaining 10 mL of water was added, and stirring was continued until a homogeneous paste was formed.

### 2.2.4. Clay modification in suspensions.

Modification of clay particles in suspensions by HA (5-100 mg/L) was carried out by adsorption on clays for 5 days at RT.

### 2.2.5. Modification of clay paste.

A bentonite paste modified with HA was prepared by adding the required amount of HA. The system was manually mixed for 15 minutes and then left to adsorb HA for 5 days. The clay content in the paste was 14.5%. The HA concentration ranged from 0.01 g/L to 0.1 g/L. Chitosan (0.1 to 1.0 g/L) was added to both the modified and unmodified clay. The pH of the modified paste with the addition of chitosan was 6.0.

### 2.2.6. Modification of the glass plates.

The modification was carried out by keeping the selected pure glass plates in HA solutions for 5 days at RT. The purity of the plates was checked by the water contact angle (24-25°) on the glass plates, which were previously soaked for 10 h in a chromium mixture (concentrated sulfuric acid + potassium dichromate), washed, and boiled in distilled water for 30 min. The HS concentrations used reflect their values in natural waters. The modification conditions assume an equilibrium state of the system.

### 2.2.7. Particle sizing and zeta potential analyses.

Particle size and the zeta potential were determined by DLS using a Nano Brook Omni Particle Analyzer (Brookhaven Instruments USA).

### 2.2.8. Turbidity measurement.

Turbidity of the samples was studied using a HI 98713-02 turbidimeter (Hanna, Romania) at RT according to the protocol in the device description. Units of turbidity were Formazin Nephelometric Units (FNU). Calibration using standard formazin suspensions was performed by the manufacturer.

The clay dispersion was placed in the turbidimeter cuvette, followed by the addition of NaCl solution until the desired salinity was reached. Parameters used to compare the stability of the dispersed system were the time during which the system did not react to the presence of salt, or the salt concentration that caused coagulation within a given time period. The turbidity values remained constant in all repeated experiments (n=5) with a method accuracy of (2 FNU).

### 2.2.9. Drop shape analysis.

The drop shape of water was recorded with a photo camera connected to a computer, which displayed an image of the drop and was treated by the software “Promer (at RT). Contact angles were measured to the right and left at the interface where water, air, and solid meet, and the average value was taken (n=7). The accuracy of the method is ±1 [28].

### 2.2.10. Rheological studies of clay pastes.

Rheological studies of bentonite pastes were carried out using a Reotest 2 rotary viscometer, equipped with a system of coaxial cylinders (Messgeräte Medingen GmbH, Germany). Operating shear rate range was: 0.2–4.86•10^3 $s^{-1}$. Strain rate (1/sec) control was carried out manually. The shear stress (Pa) readings were recorded on the device.

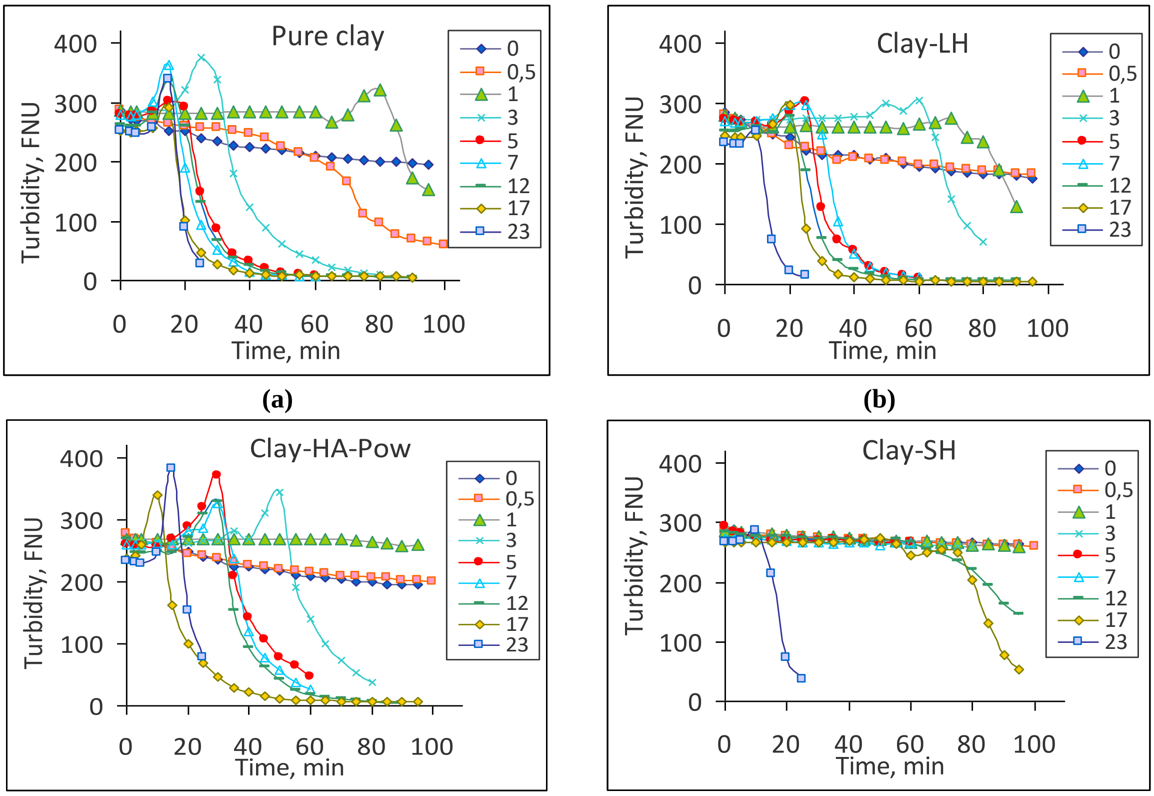
## 3. Results and Discussion

### *3.1. The influence of different humic substances and salinity on the stability of organomineral dispersions.*

Organo-mineral interactions are the basis for the stabilization of OM in soils. They create soil structure, increase the resistance of organic compounds to decomposition and mineralization, and reduce $CO_2$ emissions into the atmosphere. Despite the importance of this issue, the mechanisms underlying OM stabilization in soils remain poorly understood. According to some views, there is the formation of a hydrophobic zone on the mineral surface (zonal concept of organomineral interactions) [29]. Another researcher focuses on the sorption of nitrogen-rich components of OM directly onto mineral particle surfaces [30] or on the formation of surface structures due to hydrophobic interactions of humic substances with mineral surfaces [20]. It is also possible to consider the formation of soil structure from the perspective of adsorption-flocculation interactions, which reflect the relationship between living and inert matter in nature: mineral particles serve as inert matter, and in situ-appearing PE of living matter acts as a flocculant. HS adsorbed on mineral particles acts as a link between them.

The occurrence of organo-mineral complexes depends on many factors; the presence of salt has a significant influence, as it leads to the entry of a large pool of labile organic matter due to salt stress on the biota. This process is observed in natural conditions in the mixing zones of sea and river waters, where sedimentation of river suspension occurs with the formation of deltas with fertile soils. In order to study the mechanism of the process, we used model systems. We have previously shown that HS are capable of stabilizing clay suspensions and colloids with the addition of salt in natural conditions [31]. Moreover, the concentrations that lead to flocculation in model systems are in good agreement with those observed in field conditions at the river-sea mixing zone, based on bioproduction estimates [32]. In this work, we have investigated the effect of various types of humic substances - Lignohumate (LH), Coal humic acids (HA-Pow), and Sakhalinsky humate (SH) on the stability of organo-mineral dispersions at different salinities. All studied HA are known as soil conditioners [33, 34].

The turbidity values of the samples may indicate the formation of organo-mineral complexes and their colloidal stability. The dependence of the turbidity of pure bentonite dispersion over time at different salinities is shown in Figure 1(a). As can be seen from the graph, the turbidity of the dispersion of pure clay in the absence of salt gradually decreases with time (from 290 to 230 FNU in 100 min). The addition of salt (0.5‰) causes no change in the turbidity until 25 min, and then the decrease in turbidity is observed, followed by a sharp decrease after 70 min. These data reflect the coagulation process and associated particle sedimentation. An increase in salinity above 3‰ leads to a decrease in the onset of coagulation time. The behavior of unmodified bentonite is fully consistent with the classical concepts of the DLVO theory, when an increase in the concentration of the electrolyte leads to compression of the double electrical layer of particles and causes their coagulation. The decrease in the zeta potential of colloidal montmorillonite with increasing salinity from -40 mV (at 0‰) to -13 mV (at 7‰) is presented in the work [35].



(a) (b)

(c) (d)

**Figure 1.** Turbidity of a bentonite dispersion as a function of time at different salinities, where **(a)** Pure bentonite; **(b)** LH modified bentonite; **(c)** HA-Pow modified bentonite; **(d)** SH modified bentonite. The numbers in the legend indicate salinity values in ‰.

However, the behavior of the bentonite dispersion changes when bentonite particles are modified with various HS with the formation of organo-mineral complexes. All the studied humates stabilize bentonite dispersion to varying degrees with increasing salinity.

As can be seen from Figure 1(b), modified LH bentonite does not exhibit the ability to coagulate at salinity 0.5‰: its coagulation begins at 3‰ after 60 min, although in the case of pure bentonite, the coagulation begins after 30 min (Figure 1(a)). As can be seen from Figure 1(c), HA isolated from brown coal (HA-Pow) is a better stabilizer: coagulation begins only at salinity 3‰ and takes 20 min longer than the coagulation of pure clay.

This trend is even more evident in the case of bentonite modified by Sakhalin humate (SH), coagulation of which begins only at 12‰ after 80 minutes (Figure 1(d)).

The data on turbidity values for three clay modifiers show that SH is the best modifier for stabilizing bentonite dispersion, followed by HA-Pow and LH (Table 1).

**Table 1.** Coagulating ability of the studied humic modifiers.

| **Type of clay** | **Salinity of the onset of coagulation ‰** | **Time of the onset of coagulation at 7‰, min** |
|---|---|---|
| Pure clay | 0.5 | 10 |
| Clay-LH | 1.0 | 25 |
| Clay-HA-Pow | 3.0 | 30 |
| Clay-SH | 17.0 | >100 |

Thus, modification of clay particles with HA inhibits DLVO-driven aggregation. This can occur through the formation of a structural-mechanical barrier (according to P.A. Rehbinder) or through an increase in the particles' zeta potential upon HA modification [28].

The composition of HA-Pow isolated from leonardite is characterized by a lower aromaticity index (10%) compared to SH (16%) and enriched with oxygen-containing compounds [34]. HA represents approximately half of the OM of SH, while the percentage of HA in $C_{org}$ of LH is only 34%. The optical characteristics of SH compared to LH indirectly indicate the former's higher molecular weight [33]. It is known that substances with higher molecular weight are stronger stabilizers of colloidal dispersions due to the formation of a structural mechanical barrier. This is confirmed by the results obtained, as the organo-mineral complex of clay with SH is more resistant to the action of salt (Figure 1 (d)).

### *3.2. Modeling of hydrophilization/hydrophobization of the surface of mineral particles.*

Along with the factors of stabilization of dispersed systems mentioned above (electrostatic and structural-mechanical), it is also important to take into account the reduction in surface energy due to the adsorption of compounds that increase the affinity for the dispersion medium. So, hydrophilization of the mineral surface typically facilitates the stabilization of dispersions. In our study, the surface of the glass plate simulates the surface of a clay mineral particle, and the HS coating of the glass plate simulates the formation of an organo-mineral complex. To evaluate the modification of the glass plate by HA, the contact angle measurement method was used. Humic substances have a diphilic nature. Small contact angle values suggest that the surface is hydrophilic. Surface hydrophilization was revealed in the case of a glass plate modified with SH regardless of its concentration.

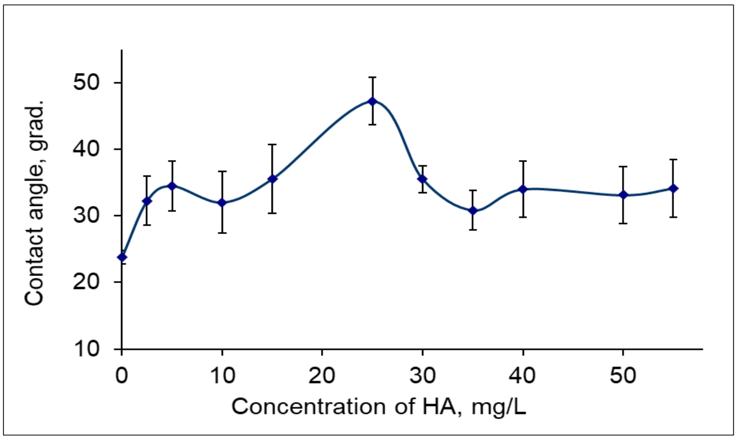
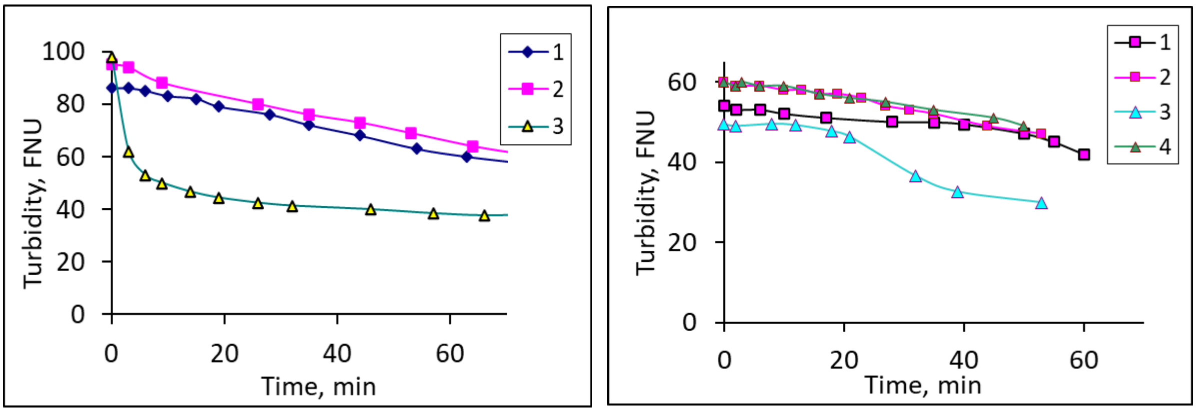


**Figure 2.** Effect of HA-Pow concentration on the contact angle of a water droplet on a modified glass plate.

The modification of the plate with HA-Pow revealed that with an increase in HA concentration to 25 mg/L, the contact angles increase, which indicates hydrophobization of the plate surface (Figure 2). The maximum on the curve may be associated with the formation of the second HA layer, in which the hydrophilic groups are oriented away from the plate surface, and the hydrophobic groups of HA interact with the molecules of the first layer due to hydrophobic interactions. Thus, this process is influenced not only by the origin of the HS but also by its concentration. It is interesting to note that we observed extreme HA concentration dependence in our turbidity experiments.These data are consistent with the results presented in the work [35], in which, based on measuring the size of montmorillonite aggregates at increasing salinity, an extreme dependence on the concentration of HA was also found.

### *3.3. Modeling of flocculation of clay particles.*

The above data on the turbidity of pure and HA-modified bentonite dispersions (Figure 1 (a–d)) may suggest the possibility of small clay particles of river runoff overcoming the mixing zone and passing into the marine environment. However, most of the mineral suspensions settle in the delta zones, which can occur in the case of weak protection of mineral particles by HS, as well as due to their flocculation (when particles interact not directly with each other, as in coagulation, but through a flocculant bridge). An increase in the ionic strength of solutions with the addition of salt in mixing zones leads to the release of labile OM capable of acting as a flocculant. This occurs due to the lysis of biota cells under salt stress. Thus, clay dispersion is destabilized both due to coagulation (addition of salt) and flocculation (with labile OM). In our study, labile OM was chitosan. Figure 3(a) shows that with the addition of chitosan to HA-Pow modified bentonite, flocculation occurs and the turbidity values drop sharply from 100 to 60 FNU within 5 minutes.



**(a)** **(b)**

**Figure 3. (a)** Turbidity of pure bentonite dispersion, HA-Pow modified bentonite without/with addition of chitosan as a function of time, where: 1- pure clay; 2 – modified HA-Powclay; 3 – modified HAPowclay + Ch, Ch concentration is 5 mg/L, HA concentration is 10 mg/L; **(b)** Effect of different concentrations of HA-Pow on the turbidity of a modified bentonite dispersion flocculated with chitosan as a function of time. Ch concentration is 5 mg/L. where 1- modified HAPow clay (5 mg/L HA); 2 - modified HAPow clay (50 mg/L HA) ; 3 - modified HAPow clay (5 mg/L HA) with additioh of Ch; 4 - modified HAPow clay (50 mg/L) with additioh of Ch;

Figure 3(b) shows that flocculation at low salinity (river sector of the mixing zone) occurs more intensively at HA concentrations of 5–10 mg/L (which corresponds to the HA content in river waters). At higher HA concentrations (50 mg/L) taken for modification, flocculation is not observed – the turbidity curves for HA clay and HA clay with Ch practically coincide. The obtained results are consistent with the results presented above on the extreme dependence of the contact angle on the concentration of HA. The chitosan concentration used in the experiment corresponds to that at which it functions as a flocculant, whereas higher concentrations can lead to stabilization of dispersion [36].

It is known that the presence of polymeric biomolecules in soils and clay suspensions is believed to facilitate the formation of aggregates [37]. In review [38], it was noted that extracellular polymeric substances (EPS) produced by microorganisms can enhance the aggregation of soil particles. Firstly, clay particles are united by inorganic and some organic binding agents, giving microaggregates (2–20 μm diameter), which are then glued by polysaccharides and polyuronides to form macroaggregates (>250 μm diameter). According to our view, OM acts in two ways: the newly formed OM acts as a flocculant and binds mineral particles coated with HS adsorbed on their surface. This is illustrated in Figure 3(a), which shows that the turbidity of colloidal bentonite increases when it is modified with HA and decreases more rapidly when chitosan is added to the modified bentonite, compared to a pure clay sample.

Another example of the formation of organo-mineral complexes due to the adsorption-flocculation mechanism is the strengthening of HS-modified bentonite paste with the addition of chitosan [36]. It can be seen from Figure 4 that the modification of bentonite with HA-Pow had practically no effect on the shear stress of the system, and its value did not exceed 24 N/m$^2$. The addition of Ch solution to the unmodified clay gave an increase in shear stress to 33 N/m$^2$, whereas the addition of Ch solution to the modified clay increased the shear stress to 58 N/m$^2$. Further increase in the concentration of the modifying reagent will not lead to strengthening of the system.

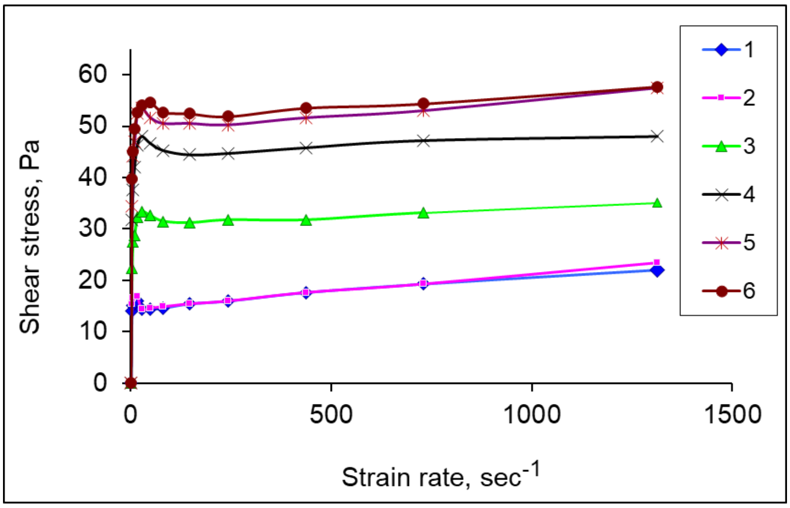


**Figure 4.** Effect of chitosan addition to pure bentonite paste and pastes modified with HA-Pow on their rheological behavior. Ch concentration is 100 mg/L, where 1 – pure clay; 2 – modified HAPow clay 10 mg/L HA); 3 – pure clay with Ch; 4 – modified HAPow clay (10 mg/L HA) with addition of Ch; 5 – modified HAPow clay (50 mg/L HA) with addition of Ch; 6 – modified HAPow clay (100 mg/L HA) with addition of Ch.

There are several types of flocculation described: bridging, patching, and sweep flocculation [39-41]. The bridging mechanism is implemented in the case of a negatively charged PE. In this case, the interaction between a negatively charged mineral particle, such as clay, and PE is carried out through positive cations. If the PE is positively charged, a second mechanism is implemented, where the interaction occurs directly due to the electrostatic attraction of the particle and the PE. If the interaction with a mineral particle occurs due to adhesion to the surface of microorganisms, or small particles are removed as a result of a high concentration of large particles, then the third type of interaction is realized [42, 43]. These types of flocculation involve the direct interaction of a particle and a PE. As shown in [44], due to their hydrophilicity, soil particles are covered with three layers of water molecules, each with a size of 8-10 Å, and the density of the first of these layers exceeds that of water. This significantly complicates the interaction of biomolecules with the clay particle surface. For this reason, weakening the hydration of clay minerals is one of the key goals in developing new polymer flocculants.

However, in nature, mineral particles in most cases are covered with layer(s) of highly transformed OM, which, being adsorbed on the particle, changes its properties. The degree of modification of river clay with OM depends on the composition of soils in the river catchment basin, the amounts of OM, and the hydrochemical characteristics of the river. The study of the influence of PE mixtures on bentonite aggregation showed that the ability to aggregate is mainly determined by the adsorption of anionic polymers [45]. Interaction of HS-modified particles with newly formed PE leads to the formation of organo-mineral aggregates.

In such formation, a layer of cationite (flocculant) is more closely pressed to the particle than a layer of polyanionite (HS), whose tails are oriented outwards. Such a structure of the complex creates conditions for further interaction between particles, both as a result of the hydrophobic effect, hydrogen bonding, and due to van der Waals interactions.

The origin of flocculants in the mixing zones and soils is poorly studied. These may be EPS produced by microorganisms, released during bacterial and viral lysis under salt stress conditions of river biota [46], as well as under salt, drought, or anthropogenic stress conditions in soils [47].

The electrostatic interaction may also be due to the electrostatic attraction of HS covering the mineral particles and cations of metals presented in water or soil [48, 49]. In the case of anionic PE, the optimum flocculant dose depends on the amount of cations present in the system. In this way, the formation of loose aggregates of dispersed particles under the action of a flocculant (flocculation) is added to the clumping of dispersed particles in the presence of electrolytes (coagulation). It is important to note that the presence of HS intensifies the process of flocculation of colloidal clay particles in comparison with the flocculation of unmodified particles [50]. The combined action of HS (inert matter) and PE (living matter) leads to the appearance of organo-mineral polymers that determine both the soil structure and therefore its fertility (in terrestrial environment) and also contribute to the formation of newly formed suspended matter in the estuaries of rivers (marine environment).

## 4. Conclusions

V.I. Vernadsky's basic concept of the biosphere is that living matter has a global impact on Earth's geochemical processes, and that life itself is nothing more than a constant exchange between inert and living matter. The natural processes of aggregation of mineral particles in the presence of organic matter in soils and in the mixing zones of rivers closely match this concept. Based on the flocculation-adsorption mechanism, it is shown that the modification of bentonite clay particles (inert matter) by humic substances increases the aggregative stability of dispersed systems even in the presence of salt. At the same time, the interaction of HA-modified particles with polyelectrolytes of biogenic origin (which occur during bacterial lysis and biota salt stress) increases the efficiency of flocculation processes compared with unmodified clays. Thus, humic substances act as an intermediate link in this process, connecting non-living and living matter and facilitating their effective interaction with the formation of organo-mineral complexes. It was found that among the humic substances studied, Sakhalin humate is better than others at stabilizing bentonite dispersions, even with increasing salinity. It has been shown that not only the nature but also the concentration of humic substances influences the aggregation with clay particles. The presented results on the interaction of clay particles with humic substances may be of interest for studying remote sensing spectra, the transport of river suspensions (and associated pollutants) at the river-sea mixing zone, and water treatment.

## Author Contributions

Conceptualization, E.A.R.; methodology, E.V.L.; investigation, E.V.L. and A.M.P.; data curation, N.A.A.; writing—original draft preparation, A.M.P.; writing—review and editing, E.A.R. and N.A.A.; supervision, E.A.R. All authors have read and agreed to the published version of the manuscript.

## Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Chemical Department Review Board of Lomonosov MSU (protocol N 112.2880.2025, date of approval 08.09.2025).

## Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

## Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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## Conflicts of Interest

The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| Abbreviation | Definition |
|---|---|
| OM | Organic Matter |
| HS | Humic Substances |
| HA | Humic Acids |
| FA | Fulvic Acids |
| Ch | Chitosan |
| Corg | Organic Carbon |
| LH | Lignohumate |
| HA-Pow | Potassium Humate |
| SH | Sakhalin Humate |
| MW | Molecular Weight |
| EPS | Extracellular Polymeric Substances |
| PE | Polyelectrolytes |
| NMR | Nuclear Magnetic Resonance |
| DLS | Dynamic Light Scattering |
| RT | Room Temperature |

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