UDC [622:531/533:65.011.8].001.3 DOI: https://doi.org/10.15407/geotm2023.166.015

DETERMINATION OF THE LIMIT CONCENTRATION OF STRUCTURED SUSPENSION ACCORDING TO THE THEORY OF LYOPHOBIC COLLOIDS STABILITY

[1]Semenenko Ye.V., [1]Medvedieva O.O., [1]Tepla T.D., [2]Medianyk V.Yu., [3]Khamynych O.V.

[1]M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, [2]Dnipro University of Technology, [3]Oles Honchar Dnipro National University

Abstract. The article investigates the influence of structured suspensions of ion-electrostatic and Van der Waals nature forces characteristics and parameters of the solid and liquid phases on the maximum achievable concentration of structured suspensions. Based on the analysis of lattice structure options formed by particles of solid phase of suspension, an assessment of possible scenarios for the disruption of the stable suspension structure has been conducted. It is shown that the least likely disruption of the stable suspension structure is the penetration of neighboring particles onto the edges of the lattice structure. The most probable disruption of the stable suspension structure is due to the penetration of particles from the nodes of neighboring lattice cells onto the diagonals lying in the planes of the faces of the considered cube, or onto the diagonals lying in the planes of the faces of this cube. This leads to a reduction in the distance between neighboring particles to values that induce irreversible and reversible coagulation processes.

A method for assessing the concentration of the equilibrium state is proposed, that is, the volumetric fraction of the solid phase in a structured suspension at which the distance between two neighboring particles corresponds to a state of stable equilibrium, depending on the value of the parameter of energy interaction between particles at different values of their effective dimensionless diameter. An estimate of the corrective coefficient of the maximum achievable concentration of suspensions was obtained, which allows determining the concentration of the suspension at which fluidity and stability are maintained, depending on the parameters of ion-electrostatic and Van der Waals forces, as well as the maximum possible volumetric concentration of the suspension. Using the formulas proposed in the work, methods for controlling the processes of preparing a structured suspension can be justified, ensuring its aggregate stability, static and dynamic sedimentation stability, by choosing the particle size and concentration of the solid phase, taking into account the parameters of ion-electrostatic and Van der Waals nature. Further development of mathematical models for controlling the stable structure of suspensions was obtained, which for the first time allows determining possible scenarios of irreversible and reversible coagulation for a given concentration and particle size of the solid phase.

Keywords: structured suspension, concentration, pipeline, inverse Debeye radius, Hamaker constant.

1. Introduction

The mining and coal industries of Ukraine offer favorable conditions for the implementation of technologies based on the stability of structured suspensions (SS) [1–7]. At mining and enrichment plants, the height of embankment dams is limited by the ability of settling ponds to clarify process water from clayey, dusty, and chalky fractions [1–3]. Coal preparation plants have the prospect of developing waste storage areas from coal enrichment as man-made deposits, with subsequent utilization as water-coal fuel (WCF), which requires ensuring aggregate stability and static sedimentation stability of these SS [4–7]. All such technologies imply a reduction in energy consumption and specific water consumption by achieving high concentrations of SS [1–3]. Therefore, to implement them, it is necessary to forecast the values of the maximum achievable concentration of suspensions (MCS), which provide aggregate stability, static and dynamic sedimentation stability of the suspension. It is very important to determine the MCS both for calculating the parameters of processes of their flow through pipelines or channels and for calculating the rheological characteristics of suspensions. In the case of WCF, it is also important for justifying the thermophysical parameters of the combustion process. Until the end of the 20th century, hydrotransport complexes and systems of mining and coal enterprises, as well as energy facilities, transported suspensions with

a concentration three or four times lower than the MCS [8]. Only in the late 20th century industrial installations of pipeline transport appeared transporting enrichment waste in the form of pastes [1, 3, 6, 9]. From the middle of the last century, issues of using WCF and backfilling mined-out space in coal mines were widely studied, in which pipeline transport of high concentration hydro-mixtures was also assumed [1, 2, 10]. Therefore, one of the first analytical estimates of the MCS, namely 52.33% by volume, was obtained for high-concentration hydro-mixtures for the technology of backfilling mined-out space in coal mines [8]

$$C_M = \frac{\pi}{6}, \tag{1}$$

where C_M – MCS, calculated from the condition of a cubic shape of the structural cell of the suspension, fractions of a unit.

Specialists of the Institute of Mining Technologies of the National Academy of Sciences of Ukraine obtained similar values of MCS for a cubic shape of the structural cell, as well as a value of MCS equal to 52.36 % by volume, for a tetrahedral-shaped structural cell [8]. Subsequently, these results were generalized in the form of a dependence of MCS on the angle between segments connecting the centers of two neighboring particles in the structural cell [11]

$$C_M = \frac{\pi}{6(1-\cos\theta)\sqrt{1+2\cos\theta}}, \tag{2}$$

where θ – the angle between the segments connecting the centers of two neighboring particles in the structural cell, degrees.

Formulas (1) and (2) were derived for homogeneous particles of solid phase of the suspension and do not take into account the interaction between particles themselves, as well as the physical parameters of their material.

Experimental results on the critical flow regimes of hydro-mixtures made of different materials with polydisperse particles of the solid phase were obtained by specialists of the Institute of Mining Technologies of the National Academy of Sciences of Ukraine [8]. In the critical flow regime of suspension through a pipeline, the liquid phase is unable to support the suspension of solid phase particles, resulting in the suspension stratifying into two layers across the cross-section. The upper layer consists of water with a low content of particles with sizes smaller than 100 μm, while the lower layer, a highly concentrated layer, is formed by particles of the solid phase that have settled on the bottom of the pipeline. As experimental studies have shown, this lower layer is characterized by maximum possible saturation with solid particles, and its volumetric concentration depends on the content of particles with sizes smaller than 100 μm [8]:

$$C_L = 0.3\left(2 - P_{0.1}\right), \tag{3}$$

where C_L – the maximum possible volume concentration of the hydro-mixture, corresponding to densely packed solid particle, fractions of a unit; $P_{0.1}$ – the mass fraction of particles with diameters smaller than 0.1 mm, fractions of a unit.

If the dependencies (1)–(3) were obtained for a suspension at rest, then for technologies involving WCF, both static and dynamic sedimentation stability of the suspension are of interest. Specialists from PRJSC SIC HYMEC (HYMEC) based on experimental data on the mobility, flowability, and aggregate stability of water-coal suspensions from coals of various grades [4–7] propose multiplying the MCS value obtained from theoretical formulas by a coefficient that depends on the volatiles content:

$$\widetilde{C}_* = C'_* K_C, \tag{4}$$

$$C'_* = \frac{\left(1 + Ar\right)C_M}{1 + ArC_M}, \tag{5}$$

$$K_C = \frac{1}{1.044 + 0.0052V^{daf}}, \tag{6}$$

$$Ar = \frac{\rho_S - \rho_0}{\rho_0}, \tag{7}$$

where $\widetilde{C}_*$ – the limiting mass concentration of SS, ensuring its mobility, fluidity, static and dynamic sedimentation stability, as well as aggregate stability, fractions of a unit; C'_* – MCS by mass, fractions of a unit; K_C – empirical correcting coefficient of MCS; V^{daf} – yield of volatile substances on the dry coal mass, fractions of a unit; Ar – Archimedes parameter; ρ_S – the average weighted density of solid phase particles, kg/m^3; ρ_0 – the density of the liquid phase, kg/m^3.

Formula (4), taking into account expression (3) as well as the relationship between the density of coals and their yield of volatile substances and ash content, was refined by specialists of the Institute of Mining Technologies of the National Academy of Sciences of Ukraine as follows [6]

$$\widetilde{C}_* = \frac{1}{1 + \dfrac{Ar}{5.36}\left(1 - \dfrac{A^d {V^{daf}}^{0.12}}{332}\right)\dfrac{2 - P_{0.1}}{P_{0.1} - 0.89}{V^{daf}}^{0.1}}, \tag{8}$$

where A^d – ash content of coal, %.

Polish specialists, during experimental studies of turbulent flow of water-limestone hydro-mixtures with solid phase particles of 45.5 μm, managed to achieve a maximum volumetric concentration of 50% [12]. The use of flocculants allowed for a reduction in hydraulic resistance in the pipeline, but did not allow to increase the MCS. Indonesian researchers, while studying the flow of slurry with different particle sizes and densities through pipelines of various diameters, achieved a maximum volumetric concentration of 40% [13]. In a study [14], the physical, chemical, and rheological properties of water-coal slurry with coal particle sizes ranging from 90 to 300 μm were investigated, and a maximum mass concentration of 60% was achieved. The impact of the concentration of mixtures of differently sized slurry particles of ash residue and fly ash mixtures on the flow characteristics of a centrifugal slurry pump has been studied in [15]. It is noted that the maximum mass concentration of the suspension did not exceed 50%.

Existing studies of SS flow processes and technologies for the use of two-phase flows in energy, mining, and industries do not consider the influence of ion-electrostatic and Van der Waals forces on the MCS, even though these forces and factors are considered crucial by some researchers for the examined particle sizes and concentrations [4, 5, 7, 16–20].

Thus, an important task is to investigate the impact of ion-electrostatic and Van der Waals forces characteristics, as well as the parameters of the solid and liquid phases, on the MCS of SS.

2. Methods of Research

According to the theory of stability of lyophobic colloids by Derjaguin – Landau – Verwey – Overbeek (DLVO), the aggregate stability and static sedimentation stability of suspensions (SS) are determined by a balance between attractive and repulsive forces of ion-electrostatic and Van der Waals nature [2–4, 21–23]. The sum of these forces, as a function of the distance between two neighboring solid phase particles in SS, is characterized by two extrema and two equilibrium points, where the function's graph intersects the x-axis. The abscissas of these extrema determine the distances between particles at which irreversible and reversible coagulation processes begin, while the equilibrium points correspond to stable and unstable states of structural equilibrium in the suspension. In this context, the equilibrium point lying between the extrema determines the distance between particles that ensures a stable state of structural equilibrium, while the point lying between the origin and the nearest extremum represents an unstable equilibrium state.

Therefore, the aggregate stability, static sedimentation stability, and dynamic sedimentation stability of SS are determined by the distance between interacting particles of the solid phase. At the same volumetric concentration of the suspension, this value depends on the size of the solid particles, as well as the parameters of the attractive and repulsive forces of ion-electrostatic and Van der Waals nature. Consequently, to maintain the structure of the suspension, its concentration, the particle size of the solid phase, and the value of their energy interaction parameter

should provide a distance between them that is close to the equilibrium point enclosed between the mentioned extrema [21–23]:

$$y'' = 2.473 \lg\left(\frac{4.162}{E}\right), \tag{9}$$

$$y'' = \chi h'', \tag{10}$$

$$E = \frac{A\chi}{24\pi\varepsilon_n\varphi_\delta^2}, \tag{11}$$

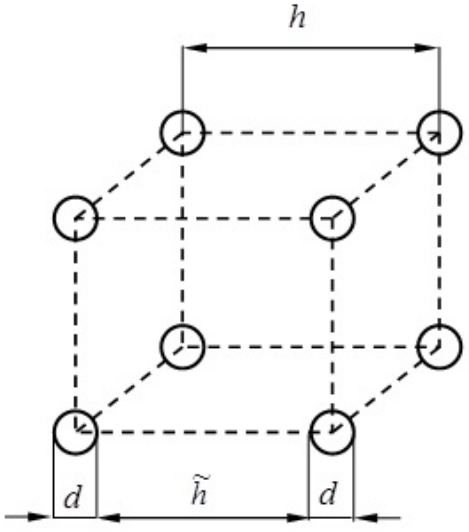
where y'' – dimensionless coordinate of the stable equilibrium point; h'' – coordinate of the stable equilibrium point, m; E – parameter of particle energy interaction; ε_n – absolute dielectric permittivity of water, F/m; φ_δ – potential of the diffuse layer of double electric charge on the surface of solid particles, V; χ – reciprocal Debye radius, m^{-1}; A – Hamaker constant, J.

Taking into account the traditional postulates of DLVO theory of lyophobic colloids, the following assumptions are made (Figure 1):

– solid particles are elastic spheres of the same diameter;

– solid particles are uniformly distributed throughout the volume of the suspension;

– distances between adjacent particles are the same in all three directions (Figure 1).



$\tilde{h}$ – distance between the surfaces of two neighboring particles, m; h – distance between the nodes of the structural lattice, m; d – diameter of solid phase particles, m

Figure 1 – Structural lattice cell with solid phase particles SS in the nodes

Under these assumptions, solid phase particles will be positioned at the nodes of a certain structural lattice with a cell equal to the distance between particles (Figure 1), and the concentration of SS will be characterized by the relationship between the following values:

$$\widetilde{h} = h - d, \tag{12}$$

where $\widetilde{h}$ – distance between the surfaces of two neighboring particles, m; h – distance between the nodes of the structural lattice, m; d – distance between the nodes of the structural lattice, m.

The difference between $\widetilde{h}$ and h is smaller the smaller the diameter of solid particles. Therefore, in the DLVO stability theory, which deals with ultrafine particles, this difference is neglected [4, 21–23]. However, this assumption's validity is not proven for SS used in technologies for hydro-mechanization of mining production, WCF and storage of mineral processing wastes as their concentrations greatly exceed those for which the DLVO theory was developed [2, 3, 24].

Since the entire volume occupied by SS is divided into elementary cells, the suspension's volumetric concentration is the same in the entire volume and in a cell. Thus, by determining the ratio of phase volumes in the cell, the volumetric concentration of SS can be found. From Figure 1, it can be seen that the volume of the solid phase in the considered cell is equal to the volume of a single particle, i.e., the volume of a sphere with a diameter d, the volume of both phases corresponds to the volume of the cell, i.e., the volume of a cube with a side length h. The ratio of these two quantities determines the volumetric concentration of SS:

$$C = \frac{\pi}{6z^3}, \qquad z = \frac{h}{d}, \tag{13}$$

the value of which can also be expressed through $\widetilde{h}$:

$$C = \frac{\pi}{6(Z+1)^3}, \qquad Z = \frac{\widetilde{h}}{d}, \tag{14}$$

where C – volumetric fraction of the solid phase in SS ($0 \le C \le 0.5$); z – step of the structural cell, expressed in diameters of solid phase particles; Z – distance between solid phase particles, expressed in their diameters.

Formulas (13) and (14) allow obtaining expressions for calculating the value of the step of the structural cell and the distance between solid phase particles depending on the concentration of SS:

$$z = \sqrt[3]{\frac{\pi}{6C}}, \qquad Z = \sqrt[3]{\frac{\pi}{6C}} - 1. \tag{15}$$

At maximum suspension saturation with solid particles, the distance between particle surfaces located at the nodes of the structural lattice will be zero, and the distance between nodes of the structural lattice will be equal to the diameter of these particles. In this case, the volumetric concentration of SS will be determined by formula (1) and correspond to the concentration filling the edge of the structural cell.

When the distance between particle surfaces located at the nodes of the structural lattice is less than the diameter of these particles, i.e., when the distance between nodes of the structural lattice is less than two diameters, the transition from a stable state of structural equilibrium in the suspension to an unstable one can only occur due to the displacement of particles from the nodes of the same cell of the structural lattice. For example, due to turbulent pulsations, oscillations of the liquid phase of the suspension, or changes in flow cross-section. Meanwhile, when the distance between particle surfaces located at the nodes of the structural lattice is equal to the diameter of these particles, i.e., when the distance between nodes of the structural lattice is equal to two diameters, another particle can fit on the edge between nodes of the structural lattice. In this case, the volumetric concentration of SS is given by:

$$C_I = \frac{\pi}{48}, \tag{16}$$

where C_I – concentration filling the edge of the structural cell, which is 6.5%.

At SS concentrations less than C_I another particle that left the node of a neighboring cell under the influence of turbulent pulsations or other external factors can fit on the edge of the structural cell. Since the structural cell has a cubic shape, there are two more dimensions that are uniquely determined by the cell step and allow placing additional solid particles (Figure 2): the diagonal lying in the planes of the cube faces (Figure 2a), and the diagonal passing through the center of the cube (Figure 2b).

The lengths of these diagonals can be easily obtained using the Pythagorean theorem for the corresponding triangles of which they are the hypotenuses:

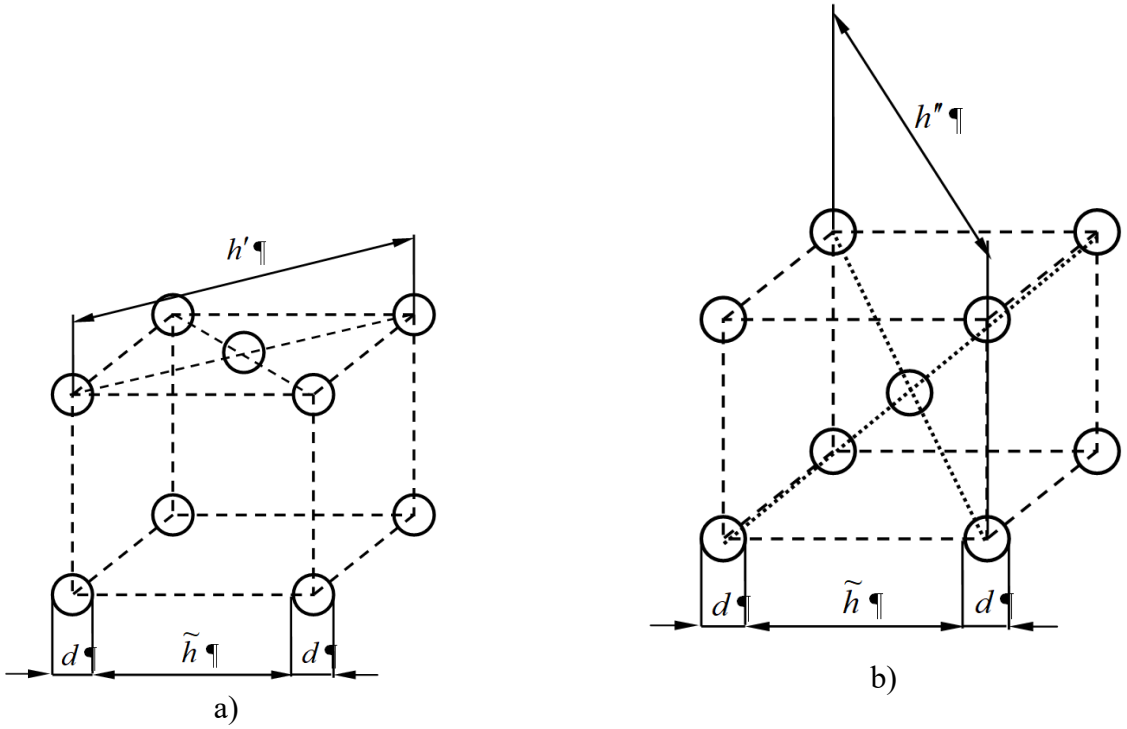
$$h' = \sqrt{2}h, \quad h'' = \sqrt{3}h, \quad h = \sqrt[3]{\frac{\pi}{6C}}d, \tag{17}$$

where h' – length of the diagonal lying in the planes of the cube faces (Figure 2a); h'' – length of the diagonal passing through the center of the cube (Figure 2b).

For these diagonals, the structural cell step expressed in the diameters of solid phase particles is proportional to the value calculated by formula (15), and will be determined by the following formulas:

$$z' = \sqrt{2}z, \quad z'' = \sqrt{3}z, \tag{18}$$

where z' – structural cell step for the diagonal lying in the planes of the cube faces; z'' – structural cell step for the diagonal passing through the center of the cube.



a) at nodes and on edges; b) at nodes and in the center of the cell

Figure 2 – Structural lattice cell with different placement of solid phase particles in SS

The corresponding values of z' and z'' distance between solid phase particles, expressed in their diameters, will be determined by the following formulas:

$$Z' = \frac{1}{\sqrt{2}}\sqrt[3]{\frac{\pi}{6C}} - \frac{1}{2}, \qquad Z'' = \frac{\sqrt{3}}{2}\sqrt[3]{\frac{\pi}{6C}} - \frac{1}{2}, \tag{19}$$

and similar to value (16), the concentration values by the following expressions:

$$C_{II} = \frac{\pi\sqrt{2}}{81}, \qquad C_{III} = \frac{\pi}{18\sqrt{3}}, \tag{20}$$

where Z' – dimensionless distance between solid phase particles for the diagonal lying in the planes of the cube faces; Z'' – dimensionless distance between solid phase particles for the diagonal passing through the center of the cube; C_{II} – concentration filling the diagonal lying in the planes of the cube faces, which is approximately 5.5%; C_{III} – concentration filling the diagonal passing through the center of the cube, which is approximately 10%.

From formulas (16) and (18)–(20) it follows that particles from the nodes of neighboring cells of the structural lattice can fit onto the diagonal lying in the planes of the considered cube faces or onto the diagonal lying in the planes of the cube faces much earlier than they can fit onto its edges. Formulas (15) and (18) can be generalized with the following relationship (Table. 1)

$$\widetilde{z} = Kz, \tag{21}$$

where $\widetilde{z}$ – generalized step of the structural cell; K – dimensionless diagonal parameter (Table 1).

Table 1 – Values of the dimensionless diagonal parameter

Parameter for calculation $\widetilde{z}$	Value of the coefficient K	Relative deviation $\frac{\widetilde{z}-z}{z}$
z	1	0.00
z'	$\sqrt{2}$	0.41
z''	$\sqrt{3}$	0.73

The suspension state will be stable if the generalized step of the structural cell, calculated using formulas (18) and (21), coincides with the coordinate of the stable equilibrium point determined by the DLFO theory, formulas (9)–(11), which is related to the diameter of the solid phase particle and the inverse Debye radius [21–23]:

$$z = \frac{y''}{\chi d}. \tag{22}$$

Considering formulas (22) and (9)–(11), together, after corresponding transformations, we obtain the following expression for calculating the volumetric fraction of the solid phase in SS, ensuring the placement of solid particles at the coordinates of the stable equilibrium points:

$$C'' = \frac{q^3}{\lg^3\left(\frac{4.162}{E}\right)}, \qquad q = \frac{K\chi d}{3.07}, \tag{23}$$

where C'' – volumetric fraction of the solid phase in SS, ensuring the placement of solid particles at the coordinates of the stable equilibrium points, fractions of a unit; q – effective dimensionless diameter of SS solid phase particles.

Using expression (23), the volumetric concentration of MCS can be determined, and to obtain the corresponding value of mass concentration, the following

expression (5) should be used:

$$\widetilde{C}' = \frac{(1+Ar)q^3}{\lg^3\left(\frac{4.162}{E}\right) + Arq^3}, \tag{24}$$

where $\widetilde{C}'$ – mass concentration of the solid phase in SS, ensuring the placement of solid particles at the coordinates of the stable equilibrium points, fractions of a unit.

Using formulas (4), (5), and (24), by equating the values of $\widetilde{C}_* = \widetilde{C}'$, we get an expression to determine the correcting coefficient through the parameters of ion-electrostatic and Van der Waals forces:

$$K_C = \frac{\frac{1}{C_L} + Ar}{\lg^3\left(\frac{4.162}{E}\right) + Arq^3} q^3. \tag{25}$$

In expression (25), instead of the value C_L, determined by formula (3), the value C_M, determined by formulas (1) or (2) can be used.

3. Results and Discussion

Calculations were performed using expressions (15), (18), (21) and (23) for cases where the values of the quantities included in these expressions vary within rationally justified limits (Table 2). The results of calculations for the step of the structural lattice expressed in the diameters of particles as a function of SS concentration for various values of the dimensionless diagonal parameter (Figure 3) indicate that the disruption of the suspension structure is least likely to occur along the edges of the structural lattice. This is because particles from the nodes of neighboring cells of the structural lattice can fit onto the diagonal lying in the planes of the considered cube faces or onto the diagonal lying in the planes of the cube faces much earlier than they can fit onto its edges.

Table 2 – Rationally justified limits of variation for quantities

Parameter	Range of variation	
	from	to
Volumetric suspension concentration	0.000	0.500
Effective dimensionless particle diameter	0.631	6.310
Particle interaction energy parameter	0.000	0.100
Dimensionless diagonal parameter	0.000	0.730
Archimedes parameter	0.140	0.280

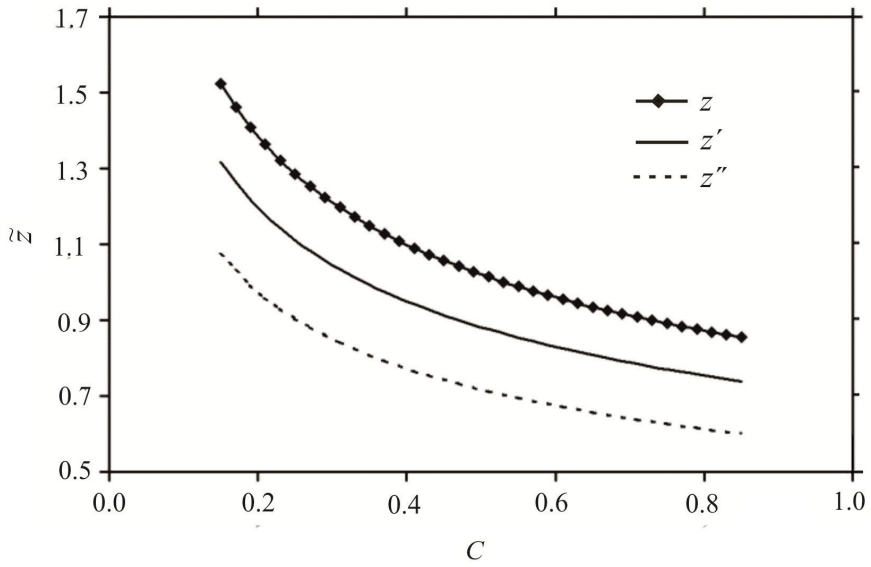


Figure 3 – Dependence of structural lattice steps expressed in particle diameters on SS concentration

The dependence of the so-called equilibrium concentration, that is, the volume fraction of the solid phase in the SS, at which the distance between two adjacent particles corresponds to a state of stable equilibrium, was investigated based on the value of the particle energy interaction parameter at different values of the effective dimensionless diameter of solid particles (Figure 4). Analysis of the graphs shows that as the value of the particle energy interaction parameter increases, the values of the equilibrium concentration increase, and larger values of the effective dimensionless diameter of solid particles correspond to larger values of concentration.

In the entire range of variation of the parameters (Table 2), the dependence of the equilibrium concentration on the value of the particle energy interaction parameter is characterized by convex curves that do not have extrema (Figure 4).

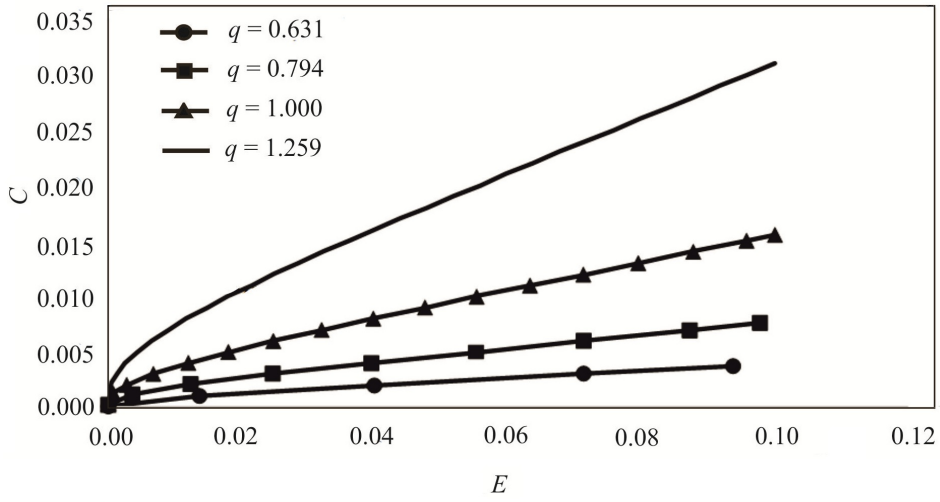
For the convenience of constructing graphical dependence of the correcting coefficient MCS on the parameters of ion-electrostatic and Van der Waals forces, let's present formula (25) in the following form (Figure 5):

$$K_C = \frac{k}{1+x}, \qquad k = 1 + \frac{1}{ArC_L}, \qquad x = \frac{1}{Arq^3}\lg^3\left(\frac{4.162}{E}\right), \tag{26}$$

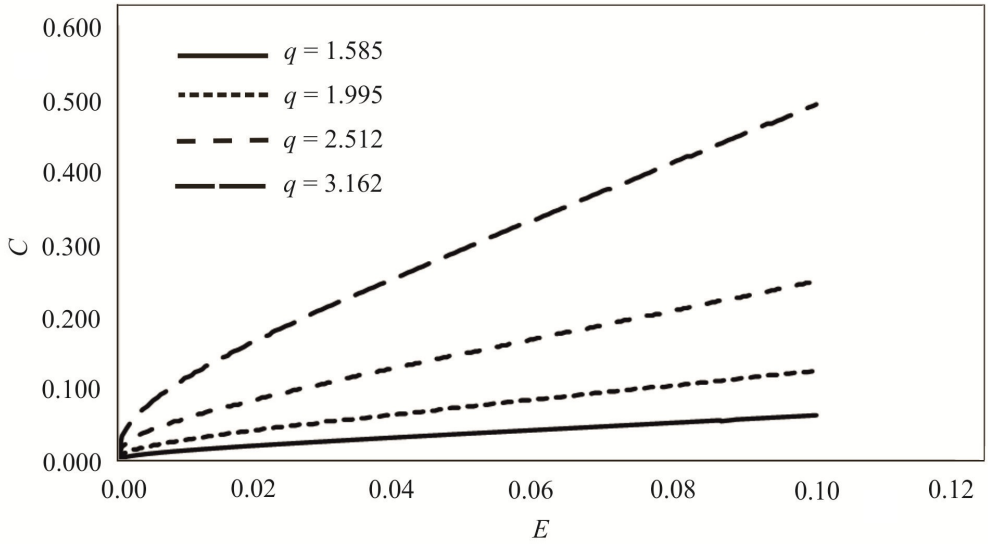
where x – parameter of equilibrium concentration; k – Parameter of the maximum possible volume concentration of SS.

The analysis of the graphs in Figure 5 shows that, across the entire range of variations in the parameters (Table 2), with the increase of the equilibrium concentration parameter, there is a decrease in the correcting coefficient MCS. Moreover, for larger values of the parameter of the maximum possible volume concentration of SS, the graphical curves are

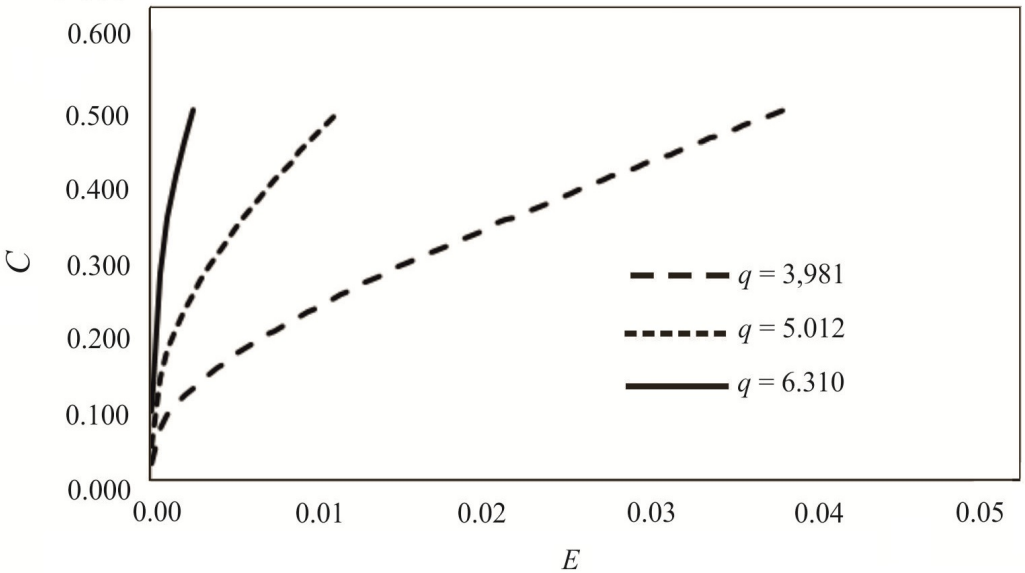
a)



b)



c)



a) – $0.631 \le q \le 1.259$; b) – $1.585 \le q \le 3.162$; c) – $3.981 \le q \le 6.310$

Figure 4 – Dependence of the volume fraction of the solid phase in SS, at which the distance between two adjacent particles corresponds to a state of stable equilibrium, on the value of the particle energy interaction parameter at different values of the effective dimensionless diameter of solid particles

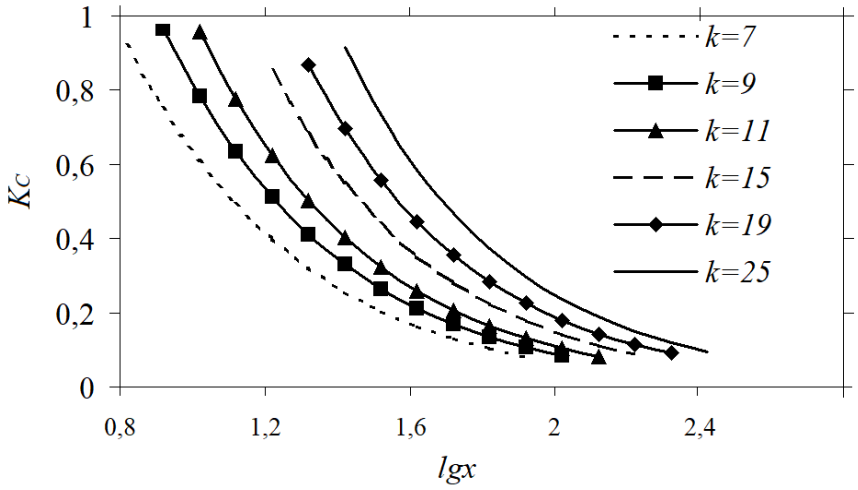


Figure 5 – Dependence of the correcting coefficient MCS on the value of the equilibrium concentration parameter at different values of the parameter of the maximum possible volume concentration of SS

positioned further away from the ordinate axis. In all cases, the dependence is decreasing, characterized by concave graphical curves without extrema. In the case where the value of the equilibrium concentration parameter, as per formula (23), becomes equal to the parameter of the maximum possible volume concentration of SS, formula (3), the value of the correcting coefficient MCS reaches its maximum value, which is one.

The obtained results indicate the necessity of further detailed study of the dependence of MCS of SS on the characteristics of ion-electrostatic and Van der Waals forces, parameters of the solid and liquid phases, as well as the rheological properties of the suspension.

4. Conclusions

This article investigated the influence of the characteristics of ion-electrostatic and van der Waals forces, as well as parameters of the solid and liquid phases, on the MCS of SS. Based on the analysis of structural lattice options formed by solid phase particles in SS, an assessment of possible scenarios of disruption of the stable suspension structure was conducted. It was demonstrated that a violation of the stable suspension structure least likely occurs through the particles entering the edges of the structural lattice. The most likely disruption of the stable suspension structure results from the particles from the nodes of adjacent structural lattice cells entering the diagonals lying in the planes of the faces of the considered cube or on the diagonals lying in the planes of the faces of this cube. This leads to a reduction in the distance between adjacent particles to values that trigger irreversible and reversible coagulation processes. A method for assessing the equilibrium concentration, i.e., the volume fraction of the solid phase in SS at which the distance between two adjacent particles corresponds to a state of stable equilibrium, depending on the value of the particle energy interation parameter at different values of their effective dimensionless diameter, was proposed. An estimation of the correcting coefficient

MCS was obtained, allowing the determination of the concentration value of SS, at which fluidity and stability are maintained, depending on the parameters of ion-electrostatic and Van der Waals forces, as well as the parameter of the maximum possible volume concentration of the suspension.

Thus, by using formulas (1) – (26), possible methods for controlling the processes of preparing of SS can be justified, ensuring its aggregate stability, static and dynamic sedimentation stability, by selecting the particle size and concentration of the solid phase particles, taking into account the parameters of ion-electrostatic and Van der Waals forces. Further development of mathematical models for controlling the stable structure of suspensions has been achieved, which, for the first time, allows the determination of possible scenarios of irreversible and reversible coagulation for a given concentration and particle size of the solid phase.

REFERENCES

1. Blyuss, B., Semenenko, Ye., Medvedieva, O., Kyrychko, S. and Karatayev, A. (2020), "Parameters determination of hydromechanization technologies for the dumps development as technogenic deposits", *Mining of Mineral Deposits*, no. 14(1), pp. 51–61. https://doi.org/10.33271/mining14.01.051

2. Medvedieva, O.O., Semenenko, Ye.V. and Medianyk, V.Yu. (2021), "Determination of the parameters of hydromechanization processes for mining and processing plants of Kryvbas", *Gornyiy zhurnal Kazahstana,* no.12, pp. 17–22.

3. Semenenko, Ye. and Kirichko, S. (2015), "Grounds of parameters of high concentrated pulps storage technologies", *Theoretical and practical solutions of mineral resources mining – Pivnyak, Bondarenco & Kovalevska (eds), Taylor & Francis Group*, London, pp. 373–377. https://doi.org/10.1201/b19901-65

4. Krut, O.A. (2002), *Vodovuhilne palyvo* [Hydrocarbon fuel], Naukova dumka, Kyiv, Ukraine.

5. SvItliy, Yu.G. and Krut, O.A. (2010), *GIdravlIchniy transport tverdih materlalIv* [Hydraulic transport of solid materials], ShIdniy vidavnichiy dIm, Donetsk, Ukraine.

6. Kyrychko, S.M. and Demchenko, T.D. (2020), *Vibir perspektivnih biotehnologiy ta obgruntuvannya tehnologichnih rishen, spryamovanih na pokraschennya ekologichnogo stanu navkolishnogo seredovischa shovisch vidhodiv vuglezbagachennya* [Selection of promising biotechnologies and substantiation of technological solutions aimed at improving the environmental condition of coal enrichment waste storage facilities], № ДР0119U102430, M.S. Poljakov Institute of Geotechnical Mechanics NAS of Ukraine, Dnipro, Ukraine.

7. Krut, A.A. (2001), "High-ash coal sludge - an additional source of energy", *Zb. naukovih prac DNTU: serija elektrotehnika ta energetika*, no. 21, pp. 34–37.

8. Semenenko, Ye.V. (2011), *Nauchnyie osnovyi tehnologiy gidromehanizatsii otkryitoy razrabotki titan-tsirkonovyih rossyipey* [Scientific bases of hydromechanization technologies for open pit mining of titanium-zircon placers], Naukova dumka, Kyiv, Ukraine.

9. Kyrychko, S.M. (2016), Justification of the parameters of the hydromechanization processes of mining operations when using high-concentration hydraulic mixtures, Ph.D. Thesis, Geotechnical and Mining Mechanics, M.S. Poljakov Institute of Geotechnical Mechanics NAS of Ukraine, Dnipro, Ukraine.

10. Medvedieva, O.O. (2021), Development of the scientific foundations of resource-saving technologies of hydromechanical development of technogenic genera, D. Sc. Thesis, Geotechnical and Mining Mechanics, M.S. Poljakov Institute of Geotechnical Mechanics NAS of Ukraine, Dnipro, Ukraine.

11. Semenenko, Ye.V., Ruban, V.D. and Podolyak, K.K. (2017), "Justification of the parameters of the bimodal granulometric composition of the solid phase of structured suspensions", *Geo-Technical Mechanics*, no. 134, pp. 76–87. https://doi.org/10.15407/geotm2017.134.076

12. Beata, Jaworska-Jó´zwiak and Marek, Dziubi´nski (2022), "Effect of deflocculant addition on energy savings in hydrotransport in the lime production process", *Energies*, no. 15(11), pp. 3869. https://doi.org/10.3390/en15113869.

13. Azis, R., Thaha, M.A. and Bakri, B. (2021), "Parameter affecting of slurry flow in perforated pipe on fluidization method to maintenance of channel", *IOP Conf. Series: Earth and Environmental Science*, no. 841 012016 https://doi:10.1088/1755-1315/841/1/012016

14. Mangesana, N., Chikuku, R.S., Mainza, A.N., Govender, I., van der Westhuizen, A.P. and Narashima, M. (2008), "The effect of particle sizes and solids concentration on the rheology of silica sand based suspensions", *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 108, pp. 237–243.

15. Kumar, S., Mohapatra, S.K. and Gandhi, B.K. (2014), "Performance Characteristics of Centrifugal Slurry Pump with Multi-sized Particulate Bottom and Fly ash Mixtures", *Particulate Science and Technology*, no. 32, pp. 466–476. https://doi.org/10.1080/02726351.2014.894163

16. Collivignarelli, M.C., Carnevale Miino, M., Bellazzi, S., Caccamo, F.M., Durante, A. and Abbà, A. (2022), "Review of rheological behaviour of sewage sludge and its importance in the management of wastewater treatment plants", *Water Practice & Technology*, vol 17, no. 1, pp. 483 https://doi.org/10.2166/wpt.2021.098

17. Hong, E., Yeneneh, A.M., Sen, T.K., Ang, H.M. and Kayaalp, A. (2018), "A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance", Advances in Colloid and Interface Science, no. 257, pp. 19-30. https://doi.org/10.1016/j.cis.2018.06.002

18. Vachoud, L., Ruiz, E., Delalonde, M. and Wisniewski, C. (2019), "How the nature of the compounds present in solid and liquid compartments of activated sludge impact its rheological characteristics", Environmental Technology (United Kingdom), no. 40(1), pp. 60-71. https://doi.org/10.1080/09593330.2017.1378729

19. Nishiguchi, K. and Winkler, M. K. H. (2020), "Correlating sludge constituents with digester foaming risk using sludge foam potential and rheology", Water Science and Technology, no. 81(5), pp. 949-960. https://doi.org/10.2166/wst.2020.180

20. Numkam, G.L. and Akbari, B. (2019), "Effect of surfactant chemistry on drilling mud performance", Journal of Petrole-um Science and Engineering, no. 174, pp. 1309-1320. https://doi.org/10.1016/j.petrol.2018.11.075

21. Semenenko, Ye.V., Demchenko, T.D. and Ryzhova, S.A. (2016), "Investigation of the dynamic sedimentation stability of structured suspensions under the action of turbulent pulsations", *Geo-Technical Mechanics*, no. 130, pp. 115–124.

22. Semenenko, Ye.V., Tepla, T.D., Medianyk, V.Yu., Roman, S.H. and Kozhantov, A. (2023), "Investigation of the dynamic sedimentation stability of structured suspensions under the action of turbulent pulsations", *Geo-Technical Mechanics*, no. 161, pp. 115 – 124.

23. Semenenko, Ye.V., Medvedieva, O.O., Tatarko, L.G., Khamynych, O.V. and Yeluzakh, M. (2023), "Influence of the properties of solid particles added to a structured suspension on its dynamic sedimentation stability", *Geo-Technical Mechanics*, no. 163, pp. 115 – 124.

24. Yahno, O.M. and Dubovitskiy, V.F. (1976), *Osnovyi reologii polimerov* [Fundamentals of polymer rheology], Vischa shkola, Kyiv, Ukraine.

About the authors

Semenenko Yevhen Volodymyrovych, Doctor of Technical Sciences (D.Sc.), Senior Researcher, Head in Department of Mine Energy Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, evs_igtm@i.ua

Medvedieva Olha Oleksiivna, Doctor of Technical Sciences (D.Sc.), Senior Researcher in Department of Ecology of Natural Resources Development, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, medvedevaolga1702@gmail.com

Tepla Tetiana Dmytrivna, Master of Science, Senior Engineer in Department of Mine Energy Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, tanialitan9@gmail.com

Medianyk Volodymyr Yuriiovych, Candidate of Technical Sciences (Ph.D.), Associate Professor, Associate Professor of the Department of Mining Engineering and Education, Dnipro University of Technology, Dnipro, Ukraine, Medianyk.v.yu@nmu.one

Khamynych Oleksandr Vasylovych, Candidate of Technical Sciences (Ph.D.), Associate Professor, Oles Honchar Dnipro National University, Dnipro, Ukraine, khaminich_a_v@i.ua

ВИЗНАЧЕННЯ ГРАНИЧНОЇ КОНЦЕНТРАЦІЇ СТРУКТУРОВАНОЇ СУСПЕНЗІЇ ЗА ТЕОРІЄЮ СТІЙКОСТІ ЛІОФОБНИХ КОЛОЙДІВ

ƛ ʝ ʤ ʥ ʣ ʦ ʅ .ɺ ., ʄ ʝ ʜɘʝ ʜʻ ɘʘʆ .ʆ ., ʊʝ ʧʣʘʊ.ɼ ., ʄ ʝ ʜʷʥʨ ɺ .ɔ ., ʍʘʤʓʥʯʆ .ɺ .

Анотація. У статті досліджено вплив на максимально можливу концентрацію суспензій структурованих суспензій характеристик сил іонно-електростатичної та Ван-дер-Ваальсівської природи, а також параметрів твердої та рідкої фаз. На основі аналізу варіантів структурних решіток, утворених частинками твердої фази суспензії, проведено оцінку можливих сценаріїв порушення стійкої структури суспензії. Показано, що найменш ймовірним є порушення стійкої структури суспензії шляхом потрапляння сусідніх частинок на ребра структурних решіток. Найбільш ймовірним є порушення стійкої структури суспензії внаслідок потрапляння частинок з вузлів сусідніх осередків структурної решітки на діагоналі, що лежить у площинах граней куба, що розглядається, або на діагоналі, яка лежить у площинах граней цього куба. Це призводить до скорочення відстані між сусідніми частинками до величин, що викликають процеси незворотної та оборотної коагуляції.

Запропоновано метод оцінки концентрації рівноважного стану, тобто об'ємної частки твердої фази структурованої суспензії, при якій відстань між двома сусідніми частинками буде відповідати стану стійкої рівноваги, залежно від величини параметра енергетичної взаємодії частинок при різних значеннях їх ефективного безрозмірного діаметра. Отримано оцінку коригувального коефіцієнта максимально можливої концентрації суспензій, що дозволить визначити величину концентрації суспензії, при якій зберігається плинність і стійкість, залеж-

но від параметрів сил іонно-електростатичної та Ван-дер-Ваальсівської природи, а також гранично можливої об'ємної концентрації суспензії. З використанням формул, запропонованих у роботі, можуть бути обґрунтовані методи управління процесами приготування структурованої суспензії, що забезпечують її агрегативну стійкість, статичну та динамічну седиментаційну стабільність, за рахунок вибору крупності та концентрації частинок твердої фази, з урахуванням параметрів сил іонно-електростатичної та Ван-дер -Ваальсівської природи. Набули подальшого розвитку математичні моделі управління стійкою структурою суспензій, які вперше дозволяють визначати можливі для заданої концентрації та крупності частинок твердої фази сценарії незворотної та оборотної коагуляції.

Ключові слова: структурована суспензія, концентрація, трубопровід, зворотній дебаєвський радіус, константа Гамакера.