

THE RELATIONSHIP BETWEEN THE MORPHOLOGICAL CHARACTERISTICS OF AGGREGATES OF SELECTED PHYTOPLANKTON ORGANISMS AND THEIR STRENGTH IN THE FLOCCULATION PROCESS

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Abstract

This article presents the results of research on the strength of *Monoraphidium contortum* and *Microcystis aeruginosa* cell aggregates, with assumption of spherical and fractal structure of the flocs. The method of computer analysis of the microscopic image was used in the research, which made it possible to determine the size and morphological parameters of phytoplankton cell aggregates formed as a result of coagulation with FeCl_3 . The equivalent diameter (d_e) and fractal dimension (D_2) of aggregates allowed us to assess the resistance of the aggregate to shear forces (G). Based on the obtained values of the strength constant (parameter γ), it was found that *M. aeruginosa* aggregates were characterized by greater strength to the action of shear forces compared to *M. contortum* aggregates. The differences in the strength of the aggregates of the studied species were more noticeable when interpreted based on the assumption of the fractal structure of the aggregates. These differences can be important in water treatment - adjusting coagulation parameters based on phytoplankton characteristics can improve process effectiveness.

Keywords: eutrophic water treatment, coagulation/flocculation, phytoplankton organisms, aggregate strength

1. INTRODUCTION

The requirements imposed on water utilities regarding the quality and safety of drinking water have changed significantly in recent years. The World Health Organization recommends that water suppliers implement so-called Water Safety Plans (WSPs) to ensure that consumers are supplied with safe water for consumption. Under the WSPs, water utilities are required to continuously monitor water quality from intake to the consumer through treatment, transmission and storage [1, 2]. Water suppliers must define and eliminate biological, chemical and physical hazards at each stage of water treatment and distribution. Achieving the WSP's primary objective of ensuring the health safety of drinking water

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requires the introduction of so-called 'barriers' that limit the inflow and occurrence of contaminants. Three main protective barriers can be distinguished along the pathway from intake to consumer: (1) sustainable management of the catchment area to protect water from an inflow of contaminants at its source, (2) use of water treatment methods based on coagulation, flocculation, separation processes and disinfection, (3) provision of a contaminant-free water distribution and storage system.

The most important barrier to protect the health of consumers in case of contamination of abstracted water with phytoplankton organisms is the use of water treatment processes characterized by high efficiency and reliability. The problem of water contamination by phytoplankton concerns water supply systems whose source of supply is surface water. The phenomenon of massive phytoplankton growth occurs in eutrophic surface waters, especially in standing water bodies. Depending on the abundance and species composition of phytoplankton organisms, changes in the organoleptic, bacteriological and physicochemical properties of the water are observed.

During the treatment of eutrophic surface waters, technological difficulties often arise due to the low efficiency of aggregation of phytoplankton cells and separation of already aggregated material. The penetration of single phytoplankton cells and their aggregates to the subsequent stages of water purification, storage and distribution generates serious problems related to the presence of pathogenic microorganisms and toxic substances. The use of disinfecting chlorination in waters containing natural organic matter, including phytoplankton, results in the formation of organochlorine compounds, the dominant group of which are trihalomethanes (THM) included to the group of potentially carcinogenic factors [3, 4, 5].

Obtaining aggregates of phytoplankton cells with a specific size distribution and morphological properties that ensure maximum efficiency of their separation, requires determining the strength of the flocs [6]. The strength of aggregates formed in the coagulation and flocculation process can be determined based on particle size changes depending on the amount of energy applied to the system, leading to the breakage of the formed flocs [7, 8, 9]. The strength of aggregates depends on their morphological structure and the strength of intermolecular bonds. Aggregates with fractal structure, characterized by irregular shape and open and porous structure, show lower strength compared to spherical aggregates with a compact structure. The size of aggregates also affects their strength of aggregates [7, 10]. According to Jarvis et al. [7] and Li et al. [10], their strength to disintegration forces decreases as aggregates increase in size. In the case of phytoplankton cell aggregates, secreted extracellular substances are an additional factor determining the strength of aggregates. The amount and chemical composition of substances accumulated on the cell's surface are characteristic of species and depend on the development phase of organisms. The viscosity of the secreted extracellular substances strengthens the structure of aggregates and increases their resistance to the effects of disintegration forces.

Changes in the size and shape of aggregates under the influence of disintegration forces can be described using image analysis techniques. The microscopic image analysis allows to characterize the spatial structure of aggregates using a few morphological parameters and fractal geometry [11, 12, 13, 14]. This method makes it possible to determine the strength of aggregates by assuming both spherical and fractal structure of particles.

2. MECHANISMS OF AGGREGATE BREAKAGE

Aggregates are disrupted and then change their size when the hydrodynamic force exerted on flocs exceeds the strength of flocs [15]. In the case of orthokinetic flocculation, the forces associated with the dynamic impact of turbulent motion (shear forces) are of the greatest importance among the forces acting on an aggregate suspended in a liquid and decisive for its disintegration. The breakage of aggregates

due to the action of shear forces (velocity gradient - G) occurs through surface erosion, which consists in the decomposition of the flocs into many particles of a much smaller size, compared to the parent particle [7]. Surface erosion is the dominant disintegration mechanism in the case of aggregates whose second and third fractal dimensions (D_2 and D_3) are close to 2 and 3, and therefore with a compact structure and high density. Low-density flocks, characterized by loose, jagged spatial structure with the value of $D_2 < 2$ and $D_3 < 3$, are susceptible to decomposition as a result of fragmentation, consisting in the breakdown of an aggregate into smaller fragments of similar size. Flocks subjected to tensile stress (pressure gradient) are frequently fragmented (Fig. 1.).

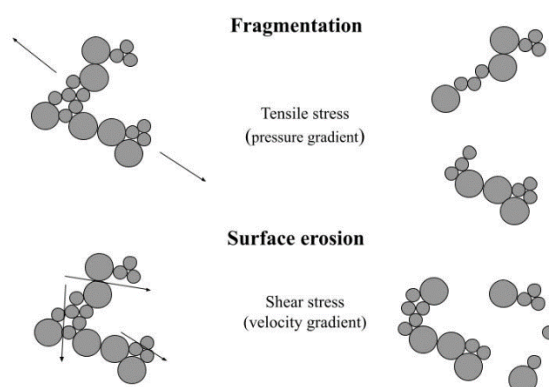


Fig. 1. Mechanisms of aggregate breakage (own elaboration based on [7])

The aim of the study was to compare the resistance of *Monoraphidium contortum* and *Microcystis aeruginosa* cell aggregates to disintegration based on changes in the size and second fractal dimension (D_2) of the flocs, under the influence of an increasing velocity gradient (G). Understanding the differences in the structure and resistance of phytoplankton aggregates can help in selecting optimal coagulation and flocculation conditions, which is crucial for the removal of biological contaminants from surface waters and for subsequent treatment processes.

3. MATERIALS AND METHODS

3.1. Phytoplankton organisms used in the research

Two species of phytoplankton organisms commonly found in eutrophic surface waters were used in the research:

- *Monoraphidium contortum* (Chlorophyta) – spindle-shaped, elongated cells, (6-18 μm in length and 2 μm in width)
- *Microcystis aeruginosa* (Cyanobacteria) – spherical-shaped cells (diameter 2.6 to 5.4 μm). Spherical, ellipsoidal colonies can reach a size of up to 8 mm.

Their presence is causing the deterioration of the physicochemical and organoleptic properties of the water [16]. *Monoraphidium contortum* and *Microcystis aeruginosa* are characterized by a different morphological structure, which allowed us to verify the influence of size and shape of cells on the spatial

structure of their formed aggregates. *M. contortum* is non-toxic, unlike *M. aeruginosa* cells, which are hazardous to health in surface waters due to the production of hepatotoxins in the form of microcystins [17, 18]. Moreover, according to Rastogi et al. [19], microcystins are a major challenge to produce safe drinking water and pose a serious threat to global public health as well as fundamental ecological processes due to their potential carcinogenicity.

Cell suspensions of *M. aeruginosa* and *M. contortum* were sourced from the University of Gdańsk (Faculty of Oceanography and Geography) and cultivated in 20-liter glass flasks under laboratory conditions. The cultivation used Z-8 medium for cyanobacteria and F/2 medium for green algae. Both phytoplankton species thrived at temperatures between 20-25°C under artificial lighting provided by an OSRAM L18W/11-860 Lumilux Plus Eco fluorescent lamp with a luminous flux of 1300 lm. The light induction period was set to 16 hours. Tests and measurements were conducted using a suspension of phytoplankton organisms diluted with distilled water at a 1:10 ratio. The use of a higher concentration of phytoplankton suspension made the morphological analysis of post-coagulation aggregates, with the use of digital analysis of the microscopic image, impossible due to the insufficient floc dispersion.

3.2. Coagulation and flocculation procedure

Polyethylene beakers with a capacity of 1000 cm³, height 130 mm and diameter 100 mm were used as flocculation chambers. The phytoplankton suspension was coagulated with iron chloride (FeCl₃ × 6H₂O). The optimal dose of FeCl₃ was 20 mg Fe³⁺·dm⁻³ and the flocculation time was 20 minutes (optimal dose and mixing time were determined based on preliminary studies). Rapid mixing was carried out at a constant rotational speed of the stirrer (100 rpm for 1 minute), while the intensity of slow mixing was variable. The pH was corrected to a constant pH of 6.0 ± 0.1. The tests were carried out at a temperature of 20.0 ± 0.1°C. In the research a JLT-6 multi-position stirrer by Velp Scientifica, using paddle mixers with dimensions of 75 × 25 mm was used. In the final phase of slow mixing, water samples containing the formed aggregates were taken from the reaction vessel and transferred to a wet cell plate. Using the method of computed microscopic image analysis, cell aggregates were characterized by selected morphological parameters.

3.3. Measurement of morphological parameters of cell aggregates

The research used the morphological parameters of the analyzed particles (cell aggregates) in the form of the diameter equivalent to the particle projection area (d_e) and length (l), which were determined using the Malvern Morphologi G3 microscopic image analyzer. It is a fully automated system that provides high-quality images and detailed analysis of particle size, shape and number. The measuring system of the Morphologi G3 analyzer includes an automatic microscope and a computer with software that enables specific analysis of the obtained results. The set is equipped with two LCD monitors - one shows the real image of particles, and the other shows the same particles transformed into a computer image. The research is in line with the requirements contained in the standardized norm *Representation of results of particle size analysis. Part 6: Descriptive and quantitative representation of particle shape and morphology* [20].

The equivalent diameter (d_e) and fractal dimension (D_2) of aggregates allowed us to assess the resistance of the aggregate to shear forces (G).

Aggregate strength was expressed using the γ coefficient, determined from the relationship between aggregate diameter and applied velocity gradient G . Higher γ values indicate greater susceptibility to disintegration, whereas lower values suggest stronger aggregates.

By analyzing both spherical and fractal structures, the study provided a comprehensive evaluation of aggregate behavior under shear forces.

The method of computer analysis of the microscopic image allows us to describe the size of phytoplankton cell aggregates using the diameter equivalent to the particle surface (d_e) (Fig. 2).

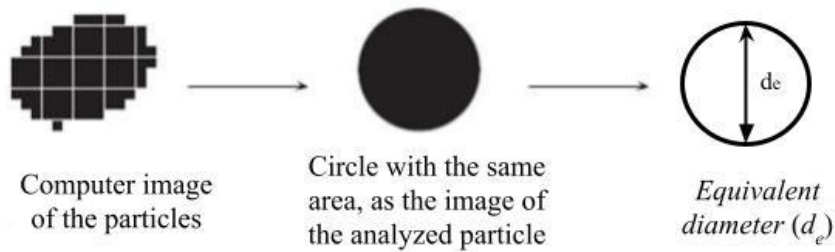


Fig. 2. Scheme for determining the equivalent diameter of aggregates (own elaboration based on [21])

The equivalent diameter (d_e) is the diameter of a circle with the same area (A) as the projection of the analyzed particle (3.1). This kind of interpretation of the test results is used even though the aggregates are not perfectly spherical [22, 23, 24, 25].

$$d_e = 2 \sqrt{\frac{A}{\pi}} \quad (3.1)$$

Having the projection area of the aggregates (A) and their maximum length (l) measured, the second fractal dimension (D_2) was determined:

$$A \propto l^{D_2} \quad (3.2)$$

The method of determining the second fractal dimension is shown in Fig. 3. The values of the D_2 dimension allow the assessment of the uniformity of the weight distribution of the aggregate from its center. The upper limit of the D_2 dimension of 2 indicates perfectly spherical particles. According to Oliveira et al. [13], particles whose D_2 tends to 0 are distinguished by an open, highly branched and loose structure, while a D_2 value close to 2 may suggest a more compact structure. A similar interpretation was presented in the work of Jiang and Logan [26] and Yuheng et al. [27] stating that particles with dimensions $D_2 < 2$ are characterized by a more porous structure.

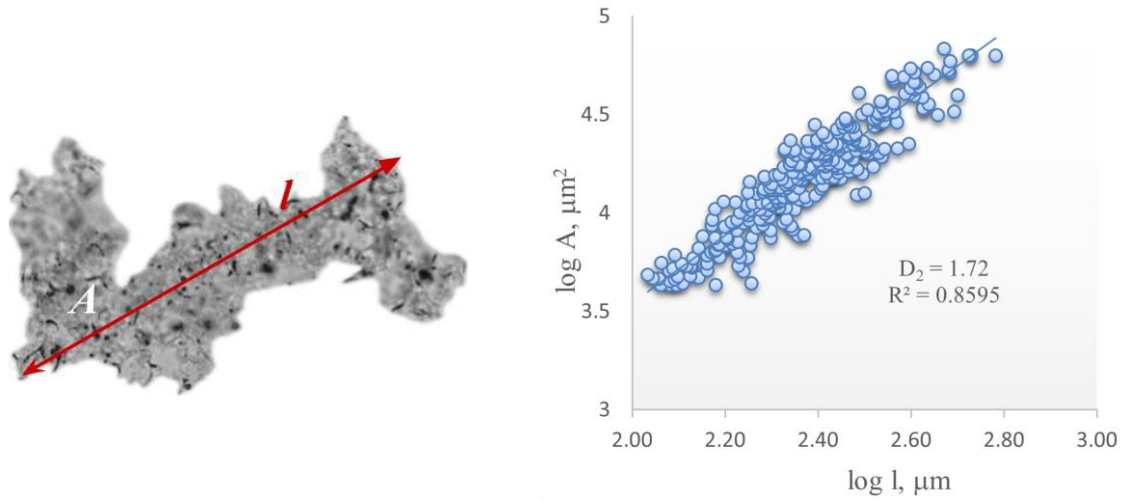


Fig. 3. The method of determining the second fractal dimension of aggregates

3.4. Determination of aggregates strength parameter

Aggregates strength constant γ can be determined based on the equation (3.3) describing the diameter of aggregates d depending on the applied velocity gradient G [7, 28, 29, 30]. In equation (3.3) C is a strength coefficient which value depends on the type of aggregated particles, coagulation/flocculation conditions, method of measuring the size of the aggregates and method of expressing their size (eg. average, maximum, median value) [-].

$$d = CG^{-\gamma} \quad (3.3)$$

The velocity gradient G was calculated using the formula in which P_m is power put into mixing [$\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-3}$], V is volume of the mixed liquid [m^3] and μ is coefficient of dynamic viscosity [$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$].

$$G = \sqrt{\frac{P_m}{\mu \cdot V}} \quad (3.4)$$

The power input into the mixing of liquids P_m was determined on the basis of the dependence taking into account the number of stirrer blades m [-] and their width b [m], liquid density ρ [$\text{kg} \cdot \text{m}^{-3}$], hydraulic resistance coefficient ζ [-], rotational speed of the stirrer n_m [s^{-1}] and the radius of the stirrer r [m]:

$$P_m = m \cdot \pi^3 \cdot \rho \cdot \zeta \cdot n_m^3 \cdot b \cdot r^4 \quad (3.5)$$

The obtained numerical values of the G velocity gradient ranged from 4 to 240 s^{-1} for stirrer rotational speeds of 10 - 150 rpm.

To determine the value of γ , the logarithm of the equation (3.3) is performed, as a result of which a linear dependence of the aggregate diameter d on the velocity gradient G is obtained:

$$\log d = \log C - \gamma \log G \quad (3.6)$$

The directional coefficient of the line obtained on the basis of the dependence (3.6) corresponds to the aggregate's strength constant γ . The greater the value of γ , the greater the susceptibility of aggregates to breakage (Fig. 4). The parameter of aggregates strength γ can assume values in the range 0.29 - 0.81 [7].

According to the authors, aggregates of kaolin particles created with the use of aluminum sulphate were characterized by γ values in the range 0.43-0.61, depending on the applied dose of the coagulant. On the other hand, the aggregates formed as a result of the coagulation of the slurry coming from the outflow of the sewage treatment plant in Bennekom (Netherlands) with the use of FeCl_3 had the values of γ from 0.26 to 0.34, depending on the manner of expressing the size of the aggregates. The highest value of the aggregate's strength ($\gamma = 0.81$) was recorded for aggregates formed during the coagulation of humic acids with aluminum sulphate. The paper also provides $\log C$ values obtained for the tested aggregates (1.9-5.9), but they should not be used to compare the aggregates' strength. The strength coefficient C can take various values depending on the type of aggregated particles, conditions of coagulation/flocculation, method of measuring size of aggregates and method of expressing their size (e.g. average, maximum, median value).

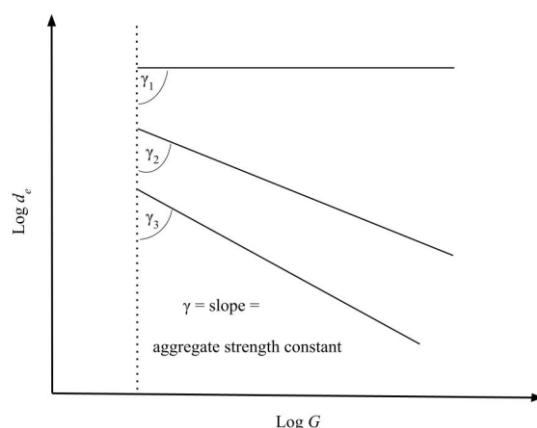


Fig. 4. Changes in the size of aggregates depending on the velocity gradient for aggregates with different strength [7]

The equation (3.3) was established on the assumption that the post-coagulation aggregates have a spherical structure. The spatial structure of aggregates is more complex and can be regarded as fractal objects. Expressing the floc morphology in terms of the fractal dimension D_n allows to describe the strength of aggregates γ_f using the equation:

$$D_n = C_f G^{-\gamma_f} \quad (3.7)$$

This proposed dependence allows for describing the differences in the strength of aggregates γ_f , resulting from the forces acting on the flocs, caused by the increasing velocity gradient G , utilizing changes in their spatial structure, not only in size.

4. RESULTS AND DISCUSSION

The most important forces acting on an aggregate suspended in a liquid, which determine its disintegration, are those related to the dynamic impact of turbulent motion and surface forces resulting from the resistance to motion. According to Gierczycki [31], in the case where the difference between the density of the particle and the liquid is small, surface forces can be neglected.

The method of computer analysis of the microscopic image used in the research allowed us to observe that the velocity gradient (shear forces) influenced on the size and spatial structure of *M. contortum* and *M. aeruginosa* cell aggregates (Fig. 5). For both phytoplankton species, with increasing

G , increasingly lower values of d_e were observed. Their spatial structure also changed and became more porous, as evidenced by decreasing D_2 values. Changes in the morphology of aggregates in the studied range of G values resulted from the interaction of hydrodynamic forces that dominated over the forces of cohesion. Shear forces (tangential) leading to the weakening of the floc structure and, consequently, to their breakdown, arose during the transfer of momentum between adjacent layers of liquid, formed under the influence of viscous forces, during mixing of the coagulated suspension. The use of paddle stirrers producing mainly circular (circumferential) liquid stream in the research resulted in the particles moving along in the direction of the current line, i.e., around the stirrer axis, changing their spatial structure into a more porous one ($D_2 < 2$). The influence of the centrifugal force acting in the direction perpendicular to the axis of the agitator in this type of agitator was insignificant.

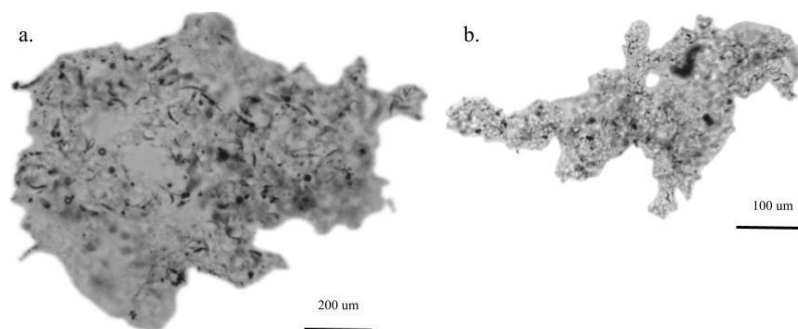


Fig. 5. Variation in the morphological structure of *M. contortum* cell aggregates depending on the mixing velocity gradient (a. $G = 4 \text{ s}^{-1}$; b. $G = 240 \text{ s}^{-1}$)

The resistance to hydrodynamic forces (dependent on the G value) depended on the strength of the intermolecular bonds of the flocs. The comparison of the strength of *M. contortum* and *M. aeruginosa* cell aggregates assuming a spherical structure of particles was made based on equation (3.3). Fig. 6 shows the linear dependence of the d_e particle size on the G velocity gradient.

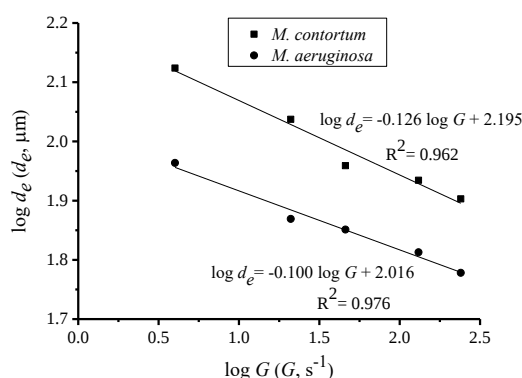


Fig. 6. Determination of the γ parameter assuming the spherical structure of particles ($D_c = 20 \text{ mg Fe}^{+3} \cdot \text{dm}^{-3}$, $t_f = 20 \text{ min.}$)

The values of γ and $\log C$ of both tested species are presented in Table 1. The obtained γ values indicated a slightly higher strength of *M. aeruginosa* cell aggregates compared to *M. contortum* flocs. The R^2 coefficient was 0.962 and 0.976, for *M. contortum* and *M. aeruginosa* aggregates, respectively.

Table 1. Comparison of strength of *M. contortum* and *M. aeruginosa* cell aggregates under the assumption of spherical and fractal floc structure ($D_c=20 \text{ mg Fe}^{+3}\cdot\text{dm}^{-3}$, $t_f=20 \text{ min.}$)

Obtained values	<i>M. contortum</i>	<i>M. aeruginosa</i>
Strength constant γ	0.126	0.100
Strength constant γ_f	0.095	0.027
$\log C$	2.195	2.016
$\log C_f$	0.289	0.306

Jarvis et al. [7] state that the value of $\log C$ is highly influenced by the method used to measure particle size and which characteristic value of d has been used. Due to significant variations across different studies, direct comparison of $\log C$ values between studies is impossible. Log C can only be used to compare floc strength within particular experimental systems [7].

Due to the fractal structure of phytoplankton cell aggregates, the comparison of their strength was also made on the basis of the equation (3.7). The spatial structure of the aggregates was expressed in terms of the second fractal dimension. The linear dependence of the second fractal dimension D_2 on the G velocity gradient is shown in Fig. 7. The values of γ_f and $\log C_f$ of both tested species are presented in Table 1. Also, in this case, the obtained values of the γ_f indicated that *M. contortum* aggregates were more susceptible to the impact of shear forces. The coefficient of matching the straight line to the experimental points R^2 was 0.909 and 0.825 for *M. contortum* and *M. aeruginosa* aggregates, respectively.

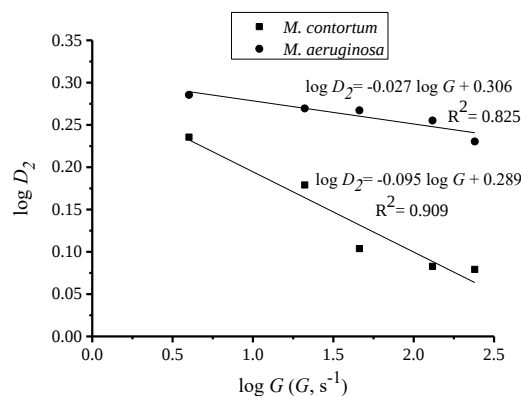


Fig. 7. Determination of the γ parameter assuming the fractal structure of particles ($D_c=20 \text{ mg Fe}^{+3}\cdot\text{dm}^{-3}$, $t_f=20 \text{ min.}$)

Based on the obtained test results, it was found that the influence of hydrodynamic forces resulting from the increasing G velocity gradient was more pronounced in the changes in the size of the flocs (higher absolute values of γ) than in the changes in their spatial structure. Comparison of the resistance of aggregates to disintegration, both assuming a spherical and fractal floc structure, indicated that *M. aeruginosa* cell aggregates were characterized by greater resistance to bursting forces. The analysis of floc strength, assuming a fractal structure of aggregates, showed greater differences between the studied

species compared to the coefficient of strength C from equation (3.3). The lower resistance of *M. contortum* aggregates to shear forces resulted from a lower solidity of flocs compared to cyanobacterial aggregates used in the research. Therefore, *M. contortum* aggregates were more susceptible to the impact of hydrodynamic forces, which resulted in their disintegration. Jarvis et al. [7] also describe the effect of aggregate compactness on their strength. The reduced breakdown resistance of the aggregates is due to the open, porous structure of the flocs. The compact structure of the aggregates proves many bonds between the primary particles and a low repulsive force between them, which translates into greater resistance of the flocs to hydrodynamic forces. According to these authors, the disintegration of aggregates is also determined by their size. The larger the size of the aggregates, the greater their susceptibility to shear forces. This assumption is confirmed by the obtained research results. *M. contortum* aggregates had higher values of mean equivalent diameter compared to *M. aeruginosa* aggregates. This is due to the significant difference in the size of the individual phytoplankton cells, whose mean equivalent diameter was 10.95 μm for *M. contortum* and 3.32 μm for *M. aeruginosa*. *M. contortum* cell aggregates with higher values of equivalent diameter showed lower resistance to bursting forces. As reported by Gonzalez-Torres et al. [32], relatively low values of the γ parameter, which indicate significant resistance of *M. aeruginosa* aggregates to degradation, result from extracellular substances secreted by cyanobacteria cells, which act as biopolymers. The mechanism of the coagulation process also affects the resistance of aggregates to shear forces [9, 10]. Li et al. [10] conducted research on the coagulation of kaolin suspension with the use of aluminum sulphate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) and polyacrylamide (PAM). The values of the γ parameter obtained by the authors of 0.37 (bridging mechanism), 0.56 (sweep type coagulation) and 0.60 (neutralization of particle charge) indicated that the aggregates formed as a result of the bridging mechanism are the most resistant to destruction, while the least are flocs formed as a result of neutralization of the charge of kaolin particles. According to the authors, this is due to the forces that bind particles in the structure of aggregates. The electrostatic interactions responsible for the binding of particles in aggregates formed as a result of charge neutralization are weaker than the bonds of polymer chains. A similar dependence was observed by Wang et al. [9] during research on the coagulation of wastewater from petrochemical industry with the use of polyiron chloride (PFC). The values of the γ parameter were 0.41, 0.45 and 0.56 for the bridging mechanism, sweep coagulation and coagulation based on the neutralization of the charge of particles, respectively. Relatively low values of the γ parameter, obtained in this study for both studied phytoplankton species, indicating a significant strength of aggregates, could result from the domination of the "sweep" coagulation mechanism over the coagulation based on the neutralization of the particle charge (the optimum pH range ensuring the lowest solubility of iron (III) hydroxide was used). This is confirmed by the photos of aggregates recorded during the study using the microscopic image analysis technique (Fig. 5). The formed flocs consisted of an amorphous hydroxide sediment with embedded phytoplankton cells, randomly distributed throughout the aggregate. Likely, the resistance to disintegration of flocs produced by "sweep" coagulation is almost entirely determined by the hydroxide sediment's nature, not by the particles contained in it. This explains the obtained, relatively small values of the γ parameters of the *M. contortum* and *M. aeruginosa* aggregates.

5. CONCLUSIONS

The paper addresses a key issue related to drinking water quality and the effectiveness of water treatment processes. It is of relevance to both environmental engineering researchers and practitioners in the water supply industry.

The work provides valuable information on the relationship between aggregate structure and resistance to hydrodynamic forces. The authors used advanced microscopic and computer analysis to accurately

determine the morphology and strength of the aggregates. Key structural parameters were taken into account, allowing a reliable assessment of the stability of the phytoplankton forms studied. Based on the results obtained, we are tempted to draw the following conclusions:

1. The differences in strength coefficient values (γ) indicate discrepancies in the resistance of aggregates of the two phytoplankton species studied to hydrodynamic forces. The lower value of γ for *M. aeruginosa* aggregates suggests their greater stability and resistance to fragmentation, which is due to their more compact structure and the presence of extracellular substances that strengthen the intercellular connections. On the other hand, *M. contortum*'s higher γ value suggests that they are more prone to disintegration, which could be because of the aggregates' looser, more porous shape. The higher the value of the fractal dimension of the particles, the less susceptible they are to decay. The smaller size of the flocs also contributed to the greater resistance of cyanobacterial cell aggregates.
2. Aggregates strength is expressed not only in their size but also in their spatial structure, expressed by D_2 .
3. Differences in strength between the studied phytoplankton species were more pronounced when interpreted based on the assumption of the fractal structure of aggregates.
4. Hydrodynamic conditions in the system (velocity gradient G) affect the size of aggregates more than their morphology.

In conclusion, this study shows that due to the fractal structure of *M. contortum* and *M. aeruginosa* aggregates, their strength can be expressed by a change not only in size, but also in the spatial structure of the flocs. Comparison of the resistance of phytoplankton cell aggregates to destruction based on changes in the value of the second fractal dimension (D_2) showed greater differences between the studied species than during the analysis of changes in the size of the flocs.

The research results are of importance for water treatment technology, especially in improving the efficiency of coagulation and flocculation processes. Understanding the differences in the structure and resistance of phytoplankton aggregates can help in selecting optimal coagulation conditions, which is crucial for removing biological contaminants from surface waters. A better understanding of aggregate decay dynamics will also improve the efficiency of applied water treatment technologies (adapting the dose of coagulants to the specific characteristics of phytoplankton aggregates and determination of optimal mixing and separation conditions), which can be applied to water supply systems.

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