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Hindered Settling of Fiber Particles in Viscous Fluids

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Abstract: In the current literature, information can mainly be found about free and hindered settling of isometric particles in Newtonian and non-Newtonian fluids. These conclusions cannot be used to describe the sedimentation of non-isometric particle in non-Newtonian fluids. For this reason, we have carried out systematic experiments and calculated the correlation of the hindered settling velocity of a cloud of non-isometric particles in high-viscosity and pseudoplastic liquid. The experiments were performed in transparent model fluids, namely, glycerine (a Newtonian fluid) and an aqueous solution of carboxylmethylcelulose CMC (a non-Newtonian pseudo-plastic liquid). These fluids have similar rheological properties, for example, the fresh fine-grained cementitious composites HPC/UHPC. The experiments were carried out with steel fibers with a ratio of d/l = 0.3/20. The settling velocity was determined for fiber volumes from 1% to 5%. While it is known from previous studies that for spherical particles the hindered settling velocity is proportional to the porosity of a suspension cloud on exponent 4.8, which was confirmed by our verification experiment, for the studied fiber particles it is proportional to the porosity on exponent 22.1. This great increase in the exponent is an effect of both the shape of the particles and, in particular, a mutual influence that arises from their interweaving and connection in the suspension.

Keywords: hindered settling velocity; non-isometric particles; steel fiber; non-Newtonian fluids; viscoplastic fluids; HPC/UHPC composites

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1. Introduction

During suspensions processing, it is necessary to have information about the particle distribution. The settling of particles in the gravitational field is the most common case. The ability to determine the settling velocity of particles in suspension is necessary when designing equipment or assessing a change in suspension composition. The basic chemical engineering calculation is simple in the case of low-concentrate suspensions formed by spherical or isometric particles. In the case of concentrated fibrous suspensions, i.e., suspensions formed by significantly non-isometric or 1D particles, the determination of the settling velocity is very complicated. Another complication is if the liquid exhibits non-Newtonian behavior.

A typical example of such suspensions is fresh fine-grained cementitious composite reinforced by distributed steel fibers. The distribution of the fibers in this matter due to particle sedimentation has an effect on the mechanical properties of constructs made from these cementitious composites. The mechanical properties of this composite are well known. During manufacturing of structures, however, fiber sedimentation and non-homogeneity of the structure can occur. The areas with minimal or non-uniform fibers have a great impact on the mechanical properties of structures and, can have a critical impact on the load-bearing capacity of constructed elements. In the existing literature, it is difficult to find information about the settling velocity of non-isometric particles which are relatively long in diameter and can become interweaved and connected. The global production of varieties of concrete mixtures which exhibit pseudo-plastic behavior is in the billions of tons per year. This means that knowledge about the hindered settling of significantly non-isometric particles in non-Newtonian pseudo-plastic liquids has a huge impact on production of HPC/UHPC structures.

For these reasons, the focus of this article is on the hindered settling of suspension clouds of non-isometric particles with a longitudinal dimension several orders of magnitude larger than their transverse dimension, specifically, with ratio d/l = 0.3/20, which are commonly used in concrete structures. These steel fibers are used as filler in modern HPC/UHPC mixtures. The fresh state of fine-grained cementitious HPC/UHPC composites exhibits the non-Newtonian behavior of a pseudo-plastic liquid.

The properties of fine-grained cementitious composites (HPC and UHPC) in both fresh and hardened states depends on the mixture's composition as well as on the type of dispersion fiber and the production technology of the concrete element (see [1–3]). The shape, size, and material properties of the fibers have a significant impact on the rheology and workability of the fresh state of the mixture. Fibers can settle the process of concrete hardens, causing non-homogeneity in the structure. For this reason, the compaction of the mixture is reduced during production of HPC/UHPC elements to prevent fiber segregation. Non-homogenous fiber distribution or its concentration in specific areas can lead to several problems in structural elements. Areas with minimal reinforcing fibers or with non-uniform reinforcement can cause structural deformation, e.g., cracks. These areas have a critical impact on the load bearing capacity of elements impacted by the homogeneity of fiber distribution and the orientation of fibers [4]. To predict the non-homogeneity of the mixture during processing, it is necessary to have a simple model describing the dependence of the settling speed of steel reinforcing particles on the concentration and flow properties of the liquid phase by modelling the behavior of the fresh concrete.

The settling velocity of one particle in an unlimited area, called the free settling velocity, can be determined from Equation (1), which is based on the balance of forces acting on a single particle [5]:

$$u = \sqrt{\frac{4}{3}\frac{D(\rho_s - \rho)g}{C_D\rho}}, \tag{1}$$

where u is the hindered settling velocity of the particle cloud, D is the characteristic particle diameter, ρ_s is the density of the particles, ρ is the liquid density, g is the gravitational acceleration, and C_D is the drag coefficient.

The hindered settling velocity is affected by the drag coefficient, C_D, as shown in Equation (1). The drag coefficient C_D of a non-spherical particle during sedimentation depends on both the shape of the particle and on its orientation. Non-spherical particles have a tendency to rotate or flip during sedimentation. For this reason, it is difficult to accurately determine the drag coefficient C_D of non-spherical particles during sedimentation. A number of authors have attempted to determine the drag coefficient of non-spherical particles.

Chhabra and Richardson [6] presented a simple relationship for the drag coefficient of cones, cubes, parallelepipeds, and axially falling cylinders in power-law fluids. Their equation is based on replacing a non-spherical particle with a given diameter with a spherical particle of the same volume. However, the authors point out that the accuracy of this relationship decreases with decreasing sphericity of the real particle. Loth [7] dealt with the drag coefficient of non-spherical particles of various shapes (regular and irregular) and for various Reynolds particle numbers in free fall. The author found that to determine the drag coefficient it is best to replace the sphericity of the particles with the aspect ratio for spheroidal particles, the surface area ratio for common non-spherical particles, and the max-med-min area ratio for very irregular particles. These substitutions apply to both high Reynolds numbers and low Reynolds numbers. However, the author points out that even with this considered substitution, the drag coefficient is determined by position of the particle at a given location during the fall; these shape substitutions are therefore only approximate, because, e.g., regularly shaped particles of different shapes with the same sphericity ratio may have different drag coefficients. Chhabra et al. [8] compared models proposed by different authors for determining the drag coefficient of non-spherical particles. The authors created a database of available data consisting of about 1900 datapoints. This database contains different particle shapes, their densities, and the different densities and viscosities of fluids covering a wide range of Reynolds numbers. The authors quantified the shape of non-spherical particles using sphericity (ranging from 0.1 for a disk to 1.0 for a sphere). The authors found that the best results were obtained using the Ganser method. This method uses the diameter of a spherical particle with equal volume as the characteristic dimension of the non-spherical particle. The authors further found that while the error of the compared methods can be 16, it can be up to 100% depending on the sphericity of the particle, with lower sphericity of the particle indicating lower agreement. In contrast to this work, Yow et al. [9] used the Kaskas equation to calculate the drag coefficient of a regular particle, which is much simpler to use and sufficiently accurate. The authors complemented this equation with coefficients dependent only on sphericity. It is clear from this research that it is not possible to precisely determine the drag coefficient of a non-spherical particle on account of the many factors affecting its size, which are most variable during a fall (especially rotation of a non-spherical particle during sedimentation). In their work, the authors recommend carrying out experiments with non-spherical particles to understand their behavior while falling before beginning separate experiments.

As mentioned above, the drag coefficient is an important parameter influencing the settling velocity. In recent years, increased attention has been paid to settling velocities in both Newtonian and non-Newtonian fluids. The settling velocity of a spherical particle in a non-Newtonian fluid was discussed by Machač et al. [10]. The authors found that low-concentration kaolin suspensions in a creep region can be considered as power-low fluids. According to the authors, much more accurate determination of the settling velocity can be obtained using the Herschel–Bulkley model. Agarwal and Chhabra [11] published results of experiments determining the settling velocity of cubes with a sphericity of 0.805 for different power law index sizes (0.61–1), consistencies, and Reynolds numbers, and verified the validity of the drag coefficient determination.

In cases of sedimentation of larger number of particles, such as the sedimentation of fibers during the processing of filled UHPC mixtures, hindered settling occurs. Furthermore, the hindered settling also occurs near the area of solid walls. In the case of industrial applications in large plants, hindered settling near the wall can be neglected in comparison with the hindered settling caused by the interaction of particles. Then, the free settling velocity must be correlated only in the presence of a larger number of particles, expressed by their concentration in the cloud of suspended particles.

The most widely used model for calculating settling velocity during hindered settling of particles is that of Richardson and Zaki [12], usually expressed as the dependence on the porosity of the suspension cloud in the form

$$\frac{u}{u_{inf}} = \varepsilon^a, \tag{2}$$

where u is the hindered settling velocity of the particle cloud, u_{inf} is the settling velocity of one particle in unlimited area, ε is the porosity of the suspension cloud and is defined on the base of the volumetric particle concentration c_v by relation $\varepsilon = 1 - c_v$, and a is the Richardson–Zaki constant. The Richardson–Zaki constant a is equal to 4.6 for hindered settling in the Stokes regime.

Kramer et al. [13] correlated the Richardson–Zaki constant and mentioned the value of the Richardson–Zaki constant as being 4.8. Di Felice and Kehlenbeck [14] verified this model on spherical particles of various materials. The same authors pointed out the need for correlation of the Richardson–Zaki constant at certain ratios of particle diameter and vessel diameter, as the settling velocity of particles is affected by the vessel wall. A generalized approach to modelling the settling velocity of spherical particles is provided in [15]. The authors used a Newtonian fluid and three non-Newtonian fluids for different Reynolds numbers along with the drag coefficient to obtain the method.

Recently, a number of works have attempted to specify the Richardson–Zaki constant in a way that it is valid for non-spherical particles. Alrawi et al. [16] determined the value of the Richardson–Zaki constant for non-spherical irregular natural sediments in a concentrated suspension. The equations of the settling velocity of spherical and non-spherical (cube, cylinder) particles in a Newtonian fluid were described in [17]. The authors found that in order to accurately determine the drag coefficient and settling velocity of non-spherical particles in a Newtonian fluid it is important to determine the shape of the particle and its orientation during settling. Furthermore, the authors created a correlation for the drag coefficient of spherical and non-spherical particles, including the effect of particle sphericity and orientation during sedimentation. The authors proposed a settling velocity equation that directly predicts the particle settling velocity of particles with different shapes and Reynolds numbers ranging from 0.471 to 1; a suitable range of particle shapes in this model includes spheres, cubes and cylinders in the ratio d:l = 1:5, 1:3, 5:1, 3:1, 1:1, 10:1. Bagheri and Bonadonna [18] investigated the influence of the shape, surface roughness, orientation, and ratio of particle density to fluid on the drag coefficient value of non-spherical particles of regular and irregular shapes in the subcritical region of the Reynolds number. They presented a general correlation of the drag coefficient under the assumption of random particle orientation in the Stokes region and Newton region. The authors found that the effect of particle orientation is significant at high values of the Reynolds number. Furthermore, they found that the drag coefficient in the Stokes region is more sensitive to changes in elongation than to changes in flatness.

2. Description of Experiments and Evaluation

2.1. Solid–Liquid Suspensions

The experiments were carried out in model transparent viscous fluids. Concentrated glycerine was used for the reference experiments to monitor the hindered settling of suspended spherical particles and fibers. The concentrated glycerine showed purely Newtonian behavior. An aqueous solution of carboxylic methylcellulose (CMC) was used to model the hindered settling of fibers in a fresh UHPC composition exhibiting pseudo- or viscoplastic behavior. Various concentrations of CMC were used to model a wide range of apparent viscosities in order to model the flow behavior of fresh UHPC mixtures with low yield stress. The composition of the model liquids was chosen to have a negligible yield stress value. The sedimentation of the tested fiber suspensions occurs when the gravitational force acting on the particles exceeds the structural forces at the flow boundary. This occurs in cases where the value of the yield stress is less than 5 Pa.

Figure 1 shows a comparison example of a rheogram of fresh state UHPC mixture (fine aggregate 1215 $kg{\cdot}m^{-3}$, silica fume 100 $kg{\cdot}m^{-3}$, slag 80 $kg{\cdot}m^{-3}$, cement 697 $kg{\cdot}m^{-3}$, water 179 $kg{\cdot}m^{-3}$, superplasticizer 40 $kg{\cdot}m^{-3}$, mass of water to concrete ratio 25.68%) with a rheogram of the model aqueous solution CMC. From this comparison, it is evident that the model CMC solution can be used as a model fluid to investigate sedimentation in fresh state UHPC mixtures. The flow properties of the fresh state UHPC mixture were measured through a method similar to that in [19]. Due to the character of fresh UHPC mixtures, all model experiments were carried out in the Stokes area of the particle flow, i.e., all values of the Reynolds number were significantly less than 0.1.

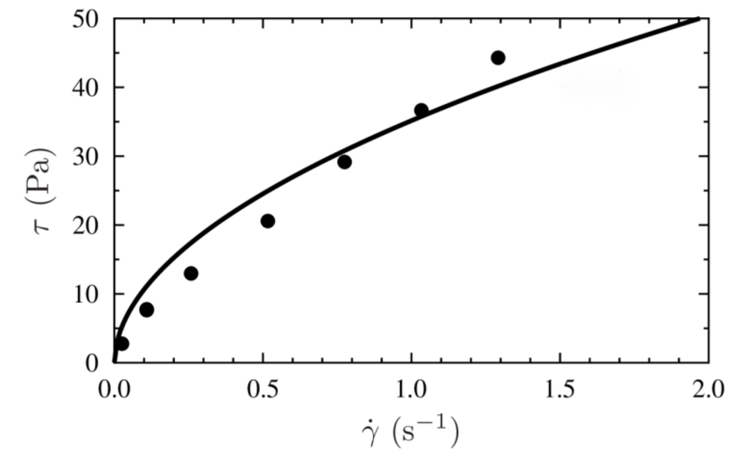

Figure 1. Comparison of the rheogram of the model CMC solution used in the experiments (solid line) with the rheogram of the fresh state UHPC mixture with a negligible value of the yield stress (points).

The sedimentation of monodisperse glass spherical particles with a diameter of 1.8 mm $\pm$ 0.1 mm and a density of 2600 kg$\cdot$m^{-3}, as well as a monodisperse mixture of steel fibers used as a filler in the UHPC mixtures, with a diameter 0.3 mm, length 20 mm, and density 7800 kg$\cdot$m^{-3}, were studied. Sedimentation in an unlimited area was monitored, i.e., sedimentation of one particle, as was sedimentation of a suspended cloud of fibers with a volume concentration up to 6.5%. The suspension was homogenized with a mechanical impeller prior to the experiment.

2.2. Sedimentation Experiments

The hindered settling velocity was evaluated through a sedimentation test. Experimental monitoring of the hindered settling of the particle cloud took place in a cylindrical vessel with a diameter of 200 mm and a filling height approximately equal to the diameter of the vessel (see Figure 2).

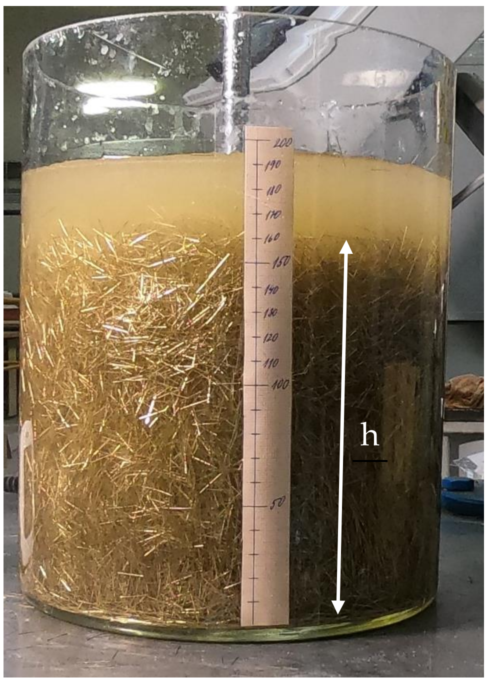

Figure 2. Layout of sedimentation test.

The settling velocity was determined from the sedimentation curve obtained by measuring the cloud height of the suspension, h (Figure 2), as a function of the settling time, indicating that the settling velocity was proportional to the direction of this dependence. The measurement was repeated at least three times for each model fluid and particle concentration. The resulting settling velocity was calculated as the average of these repeated measurements. A constant temperature was maintained during each measurement. A sample of the model liquid was taken in order to measure the flow properties during each measurement. The flow properties of all model fluids were measured using rotary rheometry via a system of coaxial cylinders on an Anton Paar MCR102 rheometer (Graz, Austria).

3. Evaluation of Particle Settlement Dependence

At least three experiments for each model fluid and particle concentration were carried out during sedimentation testing. Figure 3 shows the primary measured data on the time dependence of the height of the suspension cloud. The settling velocity was determined as the direction of the straight line for each experiment. The resulting settling velocity was calculated as the average value of the settling velocities obtained during these repeated experiments for each model fluid and particle volumetric concentration. From the evaluation of the standard deviation of repeated experiments to determine the settling velocity of the suspension cloud, the error when determining this velocity was less than 1%.

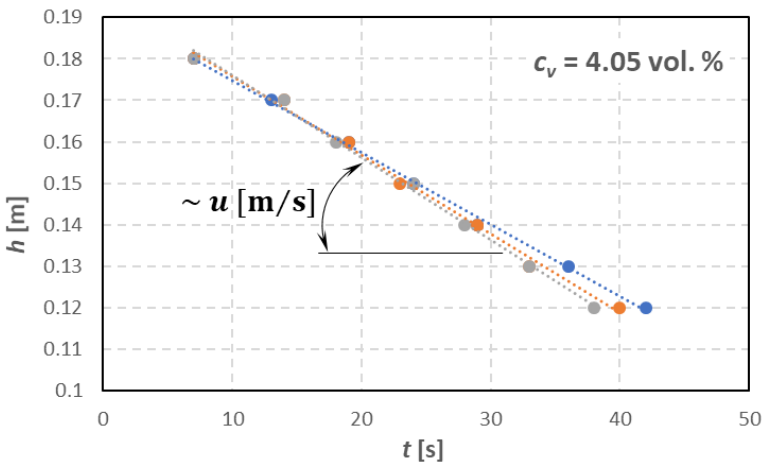

Figure 3. Illustration of the primary measured data and evaluation of the settling velocity of the particle cloud.

3.1. Monodisperse Suspension of Spherical Particles

The settling velocity of the regular spherical particles was measured in order to verify the suitability of the methodology for monitoring the hindered settling of particles in the area of the creep flow. A monodisperse suspension of spherical glass ballot particles in concentrated glycerine with a density of 1256 kg·m^{-3} and a dynamic viscosity of 1.13 Pa·s at 20 °C was used for these experiments. The settling velocity of the spherical particles in an unlimited area was measured during the experiments. This value was verified by a calculation assuming sedimentation in the Stokes regime. Furthermore, the hindered settling velocity of particles in the homogenized suspension with a volume concentration up to 6.5 vol.% was measured. The results were evaluated in the form of dependence, which was then used to describe the hindered settling in the form proposed by Richardson and Zaki (Equation (2)).

Figure 4 shows the dependence of the hindered settling of the monodisperse spherical particles in the Stokes regime on the porosity of the suspension cloud, with the porosity calculated from the mean volumetric concentration. It is evident from Figure 4 that the results obtained from this reference experiment are practically identical to the correlations for the calculation of the hindered settling velocity reported in the literature, where the value of the exponent is 4.8. This verifies the proposed methodology for monitoring hindered settling and determining the hindered settling velocity depending on the porosity or particle concentration in the suspension cloud.

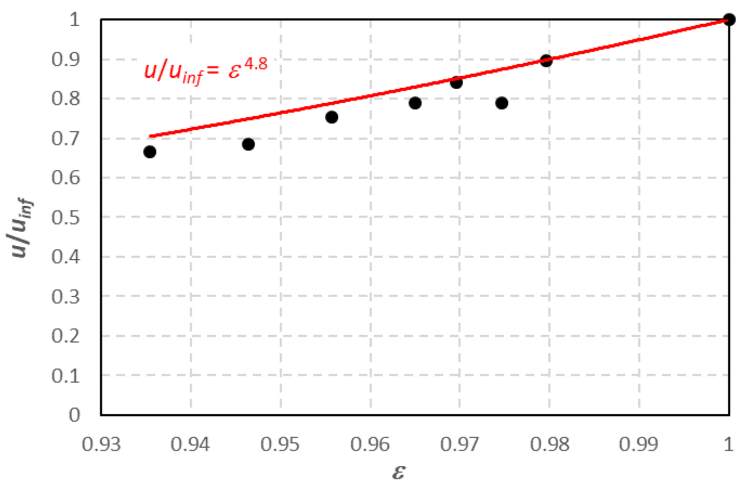

Figure 4. Hindered settling of monodisperse spherical particles in the Stokes regime in dependence on the porosity of the suspension cloud (points indicate experimental results; solid line indicates exponent in Equation (2) according to [13]).

3.2. Steel Fibers

The steel fibers used as a filler in contemporary UHPC mixers have a non-isometric shape in which the longitudinal dimension is several orders of magnitude larger than their transverse dimension, i.e., their diameter. The most common type of steel fibers used in UHPC concrete has a ratio $d/l = 0.3/20$. Thus, these are significantly non-isometric particles, for which no data or corrections can currently be found in the literature for reliable calculation of their settling velocity depending on their orientation during sedimentation. In spite of this, the possibility of using the approach of replacing the fiber with an equivalent spherical particle according to the concept of introduced sphericity was verified in the preliminary part of our experiments. The experiments were carried out in the Stokes regime showed that the settling velocity of the fiber was orders of magnitude smaller than the settling velocity of an equivalent spherical particle. This conclusion was verified for sedimentation of fibers in all particle position directions during sedimentation. For this reason, the settling velocity of one particle was monitored in detail, depending on its orientation in the liquid, for all types and flow properties of the model liquids. An example of the results of fiber sedimentation in concentrated glycerine at a constant temperature is shown in Table 1.

Table 1. Example of settling velocity of fibers depending on their position during hindered settling in glycerine with a constant temperature.

	***u* [m/s]**			
Position of the fiber insertion	–	/	|	\
Average value	0.0013	0.0014	0.0015	0.0014
Standard deviation	2.62×10^{-5}	5.41×10^{-5}	8.15×10^{-5}	4.4×10^{-5}

A more noticeable decrease in the average value of the fiber settling velocity was observed only in the case of horizontal insertion of the fibers into the liquid. However, in this case the fiber changed its orientation to a natural inclined position very quickly during the first 10% of the settling path. Similar results were obtained for all model fluids. From these results, it is clear that the orientation of the particles during sedimentation does not have a significant effect on the settling velocity in the Stokes regime, meaning that, it was possible to continue working with homogenized fiber suspensions and to monitor their behavior during hindered settling of the whole particle cloud.

Due to the fact that UHPC concrete mixtures are usually filled with fibers with a concentration of 1–3 vol.%, it is necessary to pay particular attention to the effect of the hindered settling of a monodisperse fiber particle cloud in the Stokes regime. We used the previously validated methodology for monodisperse spherical particles to describe hindered settling in this case.

Systematic experiments were carried out in transparent model liquids without significant yield flow stress. Glycerine with a dynamic viscosity of 437 mPa·s at 30 °C was used as a model Newtonian liquid. An aqueous solution of carboxymethylcellulose (CMC) in various concentrations was used to model the viscoplastic behavior of fresh UHP mixtures. The flow behavior of these CMC solutions can be described by a power-law model

$$\eta = K \cdot \gamma'^{\,n-1}, \tag{3}$$

where η is the apparent viscosity, γ' is the shear rate, K is the fluid's consistency, and n is the flow index. The flow properties of all model liquids were measured using rotary rheometry with a system of coaxial cylinders on an Anton Paar MCR102 rheometer. The model parameters according to Equation (3) for the used CMC solutions are listed in Table 2. The parameters of the power model in Equation (3) were evaluated using the least squares method.

Table 2. Parameters of the rheological model describing the flow properties of the used CMC solution.

Model Liquid	T [°C]	K [Pa·s^n]	n [-]
CMC1	23.5	19.016 ± 0.216	0.546 ± 0.007
CMC2	17.3	9.050 ± 0.131	0.748 ± 0.004
CMC3	18.4	3.315 ± 0.059	0.840 ± 0.011

In the case of hindered settling of a fiber particle cloud at lower concentrations, the fibers are initially interconnected in the layer and the initial cloud sedimentation is accelerated in comparison with the sedimentation of a single particle. This phenomenon was observed up to a concentration of about 1 vol.%. However, at concentrations greater than 1 vol.%, the expected effect of hindered settling and slowing down of the cloud settling velocity was more pronounced than for spherical particles. This described state illustrates the results of the hindered settling of fibers in concentrated glycerine, shown in Figure 5.

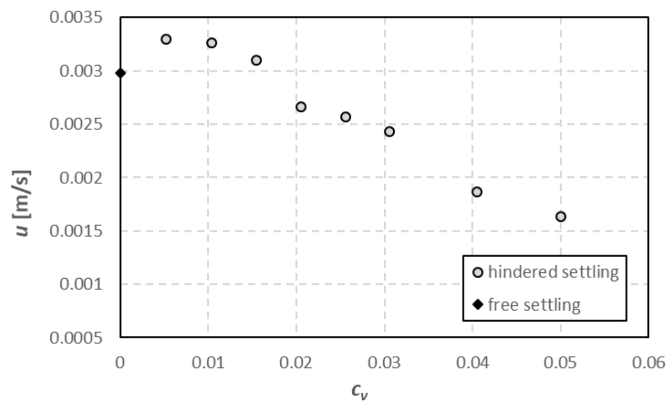

Figure 5. Settling velocity of fibers in glycerine depending on their volume concentration in the suspension cloud.

It follows from this finding that it is not possible to relate the relative velocity of hindered settling to the experimentally determined settling velocity of a single particle in an unlimited area, as is the case for isometric spherical particles. The reason for this is that the suspension cloud behaves as an interconnected layer. Systematic experiments were therefore carried out for fiber concentrations greater than 1 vol.%, in which the particles in the suspension cloud behaved compactly and unequivocally. This limitation is not an obstacle to the stated goal of monitoring fiber sedimentation in fresh UHPC mixtures, as in order to obtain a benefit in the form of better mechanical properties of concrete units made from these mixtures, the proportion of the fibers must be greater than 1 vol.%.

The dependence of the hindered settling velocity on the porosity was evaluated for every model liquid using the measurement values. This dependence was evaluated in the standard form designed by Richardson and Zaki [12] for concentrations of particles in the suspension cloud greater than the mentioned 1 vol.%:

$$u = u\prime_{inf} \varepsilon^{a}, \tag{4}$$

where u'_{inf} and the exponent a are coefficients of the power regression model.

An example of this evaluation of the cloud sedimentation of a suspension of fibers with a concentration greater than 1 vol.% in glycerine is shown in Figure 6. Subsequent evaluation of all experiments was carried out in the form of a model according to Equation (2), taking into account the fact that the relative hindered settling velocity is related to the coefficient u'_{inf} according to Equation (4). Complex results for all tested fluids evaluated according to this procedure, including confidence limits, are summarized in Figure 7.

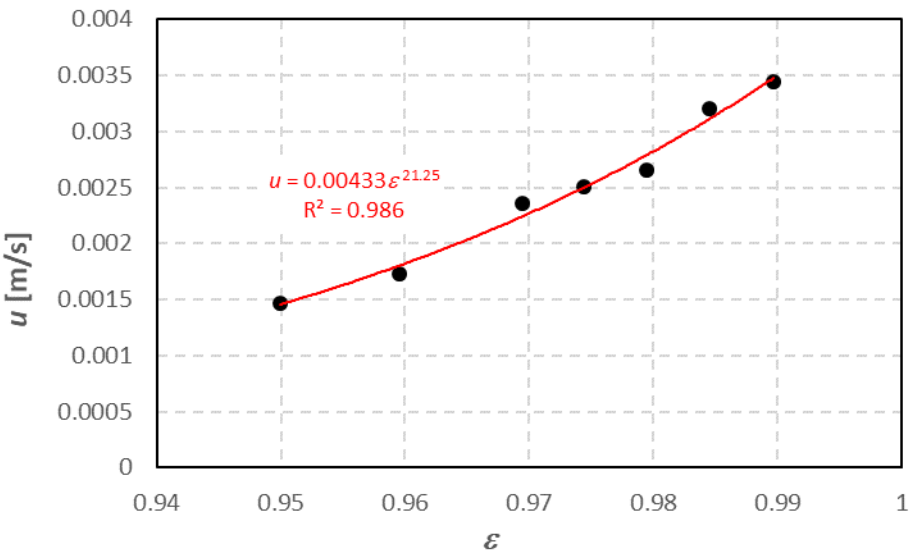

Figure 6. Evaluation of the dependence of the hindered settling velocity of the cloud of the fiber suspension on the porosity of the suspension cloud in glycerine, according to Equation (4).

The results show that in the Stokes regime of the sedimentation it is possible to describe the hindered settling of the cloud of the fiber suspension for Newtonian and pseudoplastic liquids by the following model:

$$\frac{u}{u\prime_{inf}} = \varepsilon^{22.13}. \tag{5}$$

The value of the u'_{inf} model parameter then depends on the fluid flow properties. This dependence can be expressed for a dynamic respective apparent viscosity, e.g., at a shear rate of 0.5 s^{-1}, by the power function shown in Figure 8. Similarly, the same evaluation can be performed for other shear rate values.

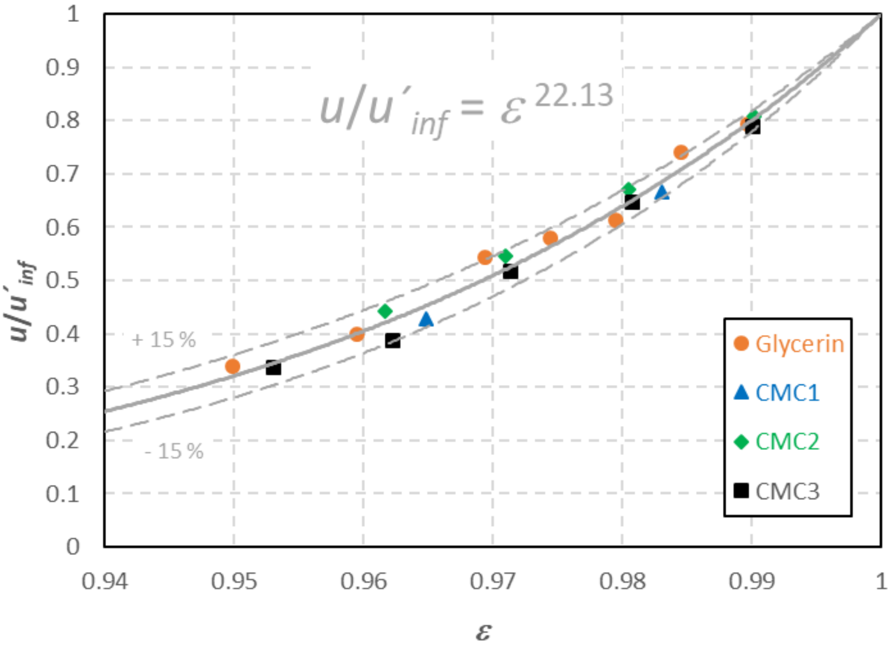

Figure 7. Dependence of the hindered settling velocity of the cloud of the fiber suspension on the porosity of the suspension cloud.

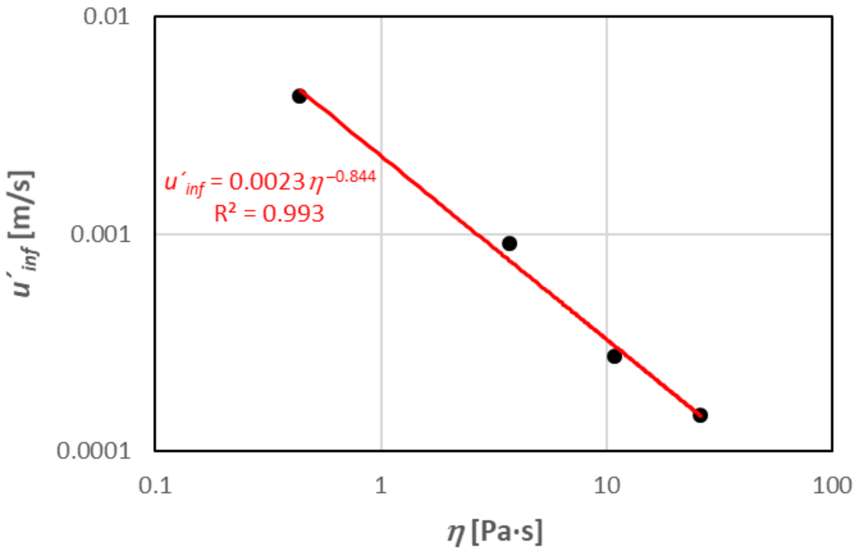

Figure 8. Dependence of the model parameter u'_{inf} according to Equation (5) on the apparent viscosity of the liquid phase of the suspension for a shear rate of 0.5 s^{-1}.

From the evaluation of the hindered settling velocity of the cloud of the fiber suspension in a wide range of liquid phase properties, it can be seen that the exponent in the Richardson–Zaki model (according to Equation (2)) or in the modified form (according to Equation (5)) is significantly higher than in the case of monodisperse spherical particles. It follows that influencing the particle sedimentation via the interaction of the fibers in the suspension is significantly more noticeable than in the case of the sedimentation of a cloud of spherical particle. It follows that it is not possible to apply the conclusions valid for the hindered settling of suspensions of isometric or spherical particles to suspensions formed by significantly non-isometric particles (in our case, the fibers), due to their interaction.

4. Conclusions

In the literature, a great deal of information can be found on the free and hindered settling of isometric particles in Newtonian fluids. In addition, several articles describe the behavior of isometric particles in non-Newtonian fluids. Based on our study of the free and hindered settling of significantly non-isometric particles, we have found that it is not possible to use these data to describe the sedimentation of such particles.

For this reason, systematic experiments were carried out to describe the hindered settling of suspension clouds of non-isometric particles with a longitudinal dimension several orders of magnitude larger than their transverse dimension (d/l = 0.3/20). Similar fibers are used as filler in modern HPC/UHPC mixtures. Experiments were carried out in transparent model fluids, namely, glycerine (a Newtonian fluid) and an aqueous solution of carboxylmethylcelulose CMC (a non-Newtonian pseudo-plastic liquid), as these have similar rheological properties to fresh HPC/UHPC mixtures. A correlation was proposed to calculate the hindered settling velocity of the cloud of these fibers depending on the porosity of the suspension and the flow properties of the liquid phase of the suspension.

First, we carried out experiments describing the settling velocity of one fiber particle depending on fiber orientation during sedimentation in the Stokes regime. Our experiments showed that the settling velocity of the fiber particle was orders of magnitude smaller than the settling velocity produced on the basis of the suggested correlation with an equivalent spherical particle. A more noticeable decrease in the average value of the fiber settling velocity was observed only in case of horizontal insertion of the fiber into the liquid, when the particle fiber changed its orientation to a natural inclined position during sedimentation.

The hindered settling velocity for the spherical particles was verified through sedimentation tests. From these experiments, we found that the hindered settling velocity of the spherical particles is proportional to the porosity with exponent 4.8. This conclusion corresponds to data previously mentioned in the literature.

The main part of this article focused on the hindered settling velocity of significantly non-isometric particles with ratio d/l = 0.3/20. The sedimentation of non-isometric particles up to the ratio d/l = 1/10 can be found in the literature. However, the conclusions mentioned in the literature cannot be used for significantly non-isometric particles due to the different behavior of these particles. In our experiments, we found that the hindered settling velocity of the used significantly non-isometric particles was proportional to the porosity more so than was the case for spherical particles, i.e., the hindered settling velocity of non-isometric particles was proportional to the porosity with exponent 22.1. The great increase in the exponent is the effect of both the shape of the particles, and in particular of the mutual influence that arises from their interweaving and connection.

These results can be applied, for example, to predict the settling velocity of fibers in fresh HPC/UHPC mixtures with negligible yield flow stress. Based on the experimentally determined apparent viscosity of fresh HPC/UHPC mixture, with a given concentration of dosing fibers it is possible to directly determine the settling velocity of the fibers from the proposed correlations, and thus to predict inhomogenous fiber distribution in concrete units due to gravitational sedimentation.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

a	Richardson–Zaki constant (Equations (2) and (4))	[-]
C_D	drag coefficient	[-]
c_v	mean volumetric concentration of particles in suspension	[-]
D	characteristic particle diameter	[m]
d	steel fibre diameter	[m]
g	gravitational acceleration	$[\mathrm{m \cdot s^{-2}}]$
h	cloud height of suspension	[m]
K	consistency coefficient	$[\mathrm{Pa \cdot s^{n}}]$
l	steel fibre length	[m]
n	flow index	[-]
u	hindered settling velocity of the particle cloud	$[\mathrm{m \cdot s^{-1}}]$
u_{inf}	settling velocity of one particle in unlimited area	$[\mathrm{m \cdot s^{-1}}]$
u'_{inf}	coefficient of the power regress model (Equation (4))	$[\mathrm{m \cdot s^{-1}}]$
ε	porosity of the suspension cloud ($\varepsilon = 1 - c_V$)	[-]
γ'	shear rate	$[\mathrm{s^{-1}}]$
η	apparent viscosity	$[\mathrm{Pa \cdot s}]$
ρ	liquid density	$[\mathrm{kg \cdot m^{-3}}]$
ρ_s	density of the particles	$[\mathrm{kg \cdot m^{-3}}]$

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