Description of solid-rich suspensions in the model of internal structure

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Abstract

Solid-rich suspensions play a crucial role in many areas of civil engineering, including fresh concrete, controlled low-strength materials, fluidized backfill materials, and bentonite support suspensions used in geotechnical applications. Due to the interaction between granular particles and the surrounding fluid phase, these materials exhibit complex rheological behavior that cannot be fully described by classical generalized Newtonian fluid models. In particular, structural changes within the granular network during deformation often lead to deviations between experimentally observed flow behavior and numerical predictions. This contribution presents a conceptual framework for describing such materials using an internal structure model. The approach introduces two phenomenological parameters: the angle of internal structure, representing the preferred orientation of contact networks and momentum transfer within the material, and a cohesive potential, describing the intrinsic ability of the granular-fluid system to maintain structural integrity. These parameters are interpreted as state variables that evolve with deformation and energy dissipation in the system. The model concept is motivated by observations from granular mechanics, rheological experiments, and structural analyses of particle networks. Experimental findings from oscillatory and rotational rheometry on solid-rich suspensions demonstrate how structural rearrangements influence energy dissipation and resistance to shear. The proposed framework aims to incorporate these structural effects into the description of momentum diffusion in the Navier–Stokes equation, thereby improving the representation of highly concentrated suspensions in analytical and numerical models. The presented concept provides a phenomenological bridge between classical continuum rheology and the evolving granular microstructure of solid-rich suspensions. Future work will focus on deriving explicit formulations for the modified momentum diffusion term and implementing the model in numerical simulations.

Introduction

Solid-rich or highly concentrated suspensions are widely used in civil engineering. Typical examples include fresh concrete, controlled low-strength materials (CLSM), and fluidized backfill materials, often referred to as liquid soils (ZFSV). Bentonite suspensions used as support fluids in geotechnical engineering also belong to this class of materials. All these materials share a common characteristic: they are multiphase systems consisting of a dispersed solid phase embedded in a continuous liquid phase. The interaction between particles and fluid gives rise to complex rheological phenomena. These include rate-independent (scleronomous) behaviors such as shear thinning, shear thickening and structural viscosity, as well as time-dependent (rheonomous) effects such as thixotropy and rheopexy. The accurate determination and parametrization of these properties, as well as their implications for material behavior, remain active areas of research. This paper provides an overview of possible interpretations of such behavior within a material model that explicitly accounts for the internal structure of solid-rich suspensions.

DOI: 10.34712/142.81-6

Controlled Low-Strength Materials (CLSM / ZFSV)

Controlled low-strength materials (CLSM), referred to in German as *zeitweise fließfähige, selbstverdichtende Verfüllbaustoffe (ZSFV)*, are highly concentrated suspensions primarily used for backfilling trenches, especially in urban construction. Immediately after mixing, these materials exhibit a fluid to plastic consistency similar to self-compacting concrete. After placement and sufficient resting time, they undergo a transition toward a consolidated state. In contrast to conventional concrete, however, the resulting structure remains comparable to that of granular soils rather than forming a rigid solid. This characteristic enables subsequent excavation without heavy equipment. In the fresh state, CLSM must satisfy two competing requirements: sufficient flowability for placement and resistance to segregation. In the hardened state, the material should exhibit mechanical behavior similar to the surrounding soil while maintaining excavability.

Historically, the characterization of these properties relied heavily on empirical index tests derived from concrete technology standards (e.g., (*DIN EN 12350-5*, 2019)). For instance, flowability was often specified solely by a target slump flow diameter (typically 50-70 cm). While such tests provide qualitative insight, they do not allow for a clear separation of influencing parameters such as density and rheological properties. In addition, the only other parameterized property was defined as the re-excavation capability via the uniaxial compressive strength.

Recent guidelines (*M ZFSV*, 2025) and (DWA-A 127-2, 2024) introduce more refined and measurable properties. In the fresh state, requirements such as suspension stability are defined, accounting for the prevention of segregation. A key parameter in this context is the yield stress, which, together with particle size and density governs stability of the suspension (Equation (1)):

$$\tau_0 = \frac{4}{3} \cdot (\gamma_{Korn} - \gamma_{Fluid}) \cdot r_{Korn} \tag{1}$$

Flowability is now categorized under both static (self-weight-driven flow) and dynamic conditions. Although still based on index tests, strong correlations between these measures and the yield stress have been observed. In addition to the new guideline (M ZFSV, 2025), the DWA-A 127-2 Worksheet Static Calculation of Drainage Systems - Part 2, 2024 sets out specific requirements for CSLM. Another important aspect is the uplift force acting on pipes embedded in CLSM. In addition to classical buoyance, a contribution arising from the yield stress acts in the flow direction (Equation (2)). Own experimental studies have shown that the buoyancy force can be up to twice as a result of the proportion of the yield point compared to the sole approach according to Archimedes.

and takes into account the special features of the building material in the static calculation. In particular, the increased buoyancy effect on the pipe when backfilled with ZFSV should be mentioned here. In addition to the conventional part of Archimedes' buoyancy, a force component acts on the tube in the direction of flow due to the yield point (equation (2)). Own investigations have shown that the buoyancy force can be up to twice as a result of the proportion of the yield point compared to the sole approach according to Archimedes.

$$f_A = \frac{\pi \cdot d_a^2}{4} \cdot \gamma_{Susp} - G_{Rohr} + 3 \cdot \pi \cdot d_a \cdot \left(\tau_f - \tau_{0,min}\right) \tag{2}$$

A major challenge remains in the determination of rheological parameters, particularly the yield stress, for highly concentrated suspensions. While methods in accordance with (*DIN EN ISO 3219-2*, 2021) are necessary to determine the rheological parameters (viscosity and yield stress); however, the prescribed test geometries only allow for particle sizes up to 0.2 mm, which is why relative rheometric methods are predominantly used in construction material rheology. Similar to the index tests described above, these relative rheometric methods allow only qualitative statements about material behavior; the exact derivation of physical parameters is therefore not directly possible. However, the modified ViscoScale test listed in (*M ZFSV*, 2025) presents an absolute rheometric method for determining the yield stress of highly concentrated suspensions. Under idealized boundary conditions, the yield stress is defined as the maximum resistance that the material can oppose the withdrawal of an anchor body. No separate distinction is made between shear-rate-dependent and static components of the resistance, even though the underlying deformation rates are kept to a minimum in the experimental setup. However, the yield stress determined in this way shows a good correlation with observable phenomena such as flow behavior and suspension stability.

In accordance with the nature of the CLSM, various analytical models and parameters are available, categorized according to the different states of the liquid soil. In the flowable state, material behavior is described strictly using parameters from classical rheology; in the solid state, soil mechanics or comparable solid-state models are applied. An attempt at a comprehensive material description is made using the model of internal structure. In the next section, the model is first introduced using basic structural concepts based on granular materials, then further specified, and its parameters and initial application are described.

Structure-descriptive approaches

It is evident that the material behavior of highly concentrated suspensions in the liquid state depends significantly on the intergranular interaction of the individual components (Figure 1). The following section presents several approaches from past studies aimed at identifying and quantifying specific contact orientations and contact frequencies in relation to their resulting effects. For the sake of simplicity, we begin with approaches from soil mechanics, which provide good insight into the underlying considerations.

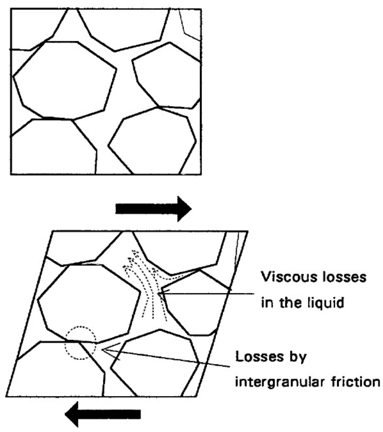

Figure 1: Influence of the granular structure at shear deformation (Ferraris' & Larrard, 1998)

Within the scientific field of soil mechanics, extensive studies have been conducted on the granular structure of regular and irregular aggregates (Guo, 2000; Oda, 1972a, 1972b, 1972c, 1974, 1993; Oda & Konishi, 1974; Wiebicke et al., 2021). The methodology of the studies involved quantifying various dry piles under a range of configurations and boundary conditions using microscopy. The quantification, for example, focused on the frequency of different contact orientations under the various boundary conditions (Figure 2 and Figure 3).

It was found that the material behavior, specifically the relationship between deformation and the stress state, depends on the internal material structure. Furthermore, it was identified that the material structure, characterized by the specific contact formation, is subject to a load-dependent change. Under load, some configurations exhibited the ability to orient contacts specifically in the direction of the dominant principal stress. The resulting loads that could be applied to the test specimen were greater than those of comparable specimens lacking this ability to change structure.

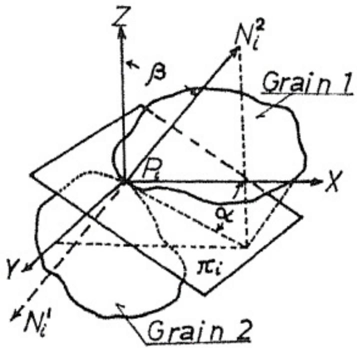

Figure 2: Contact orientation (Oda, 1972b)

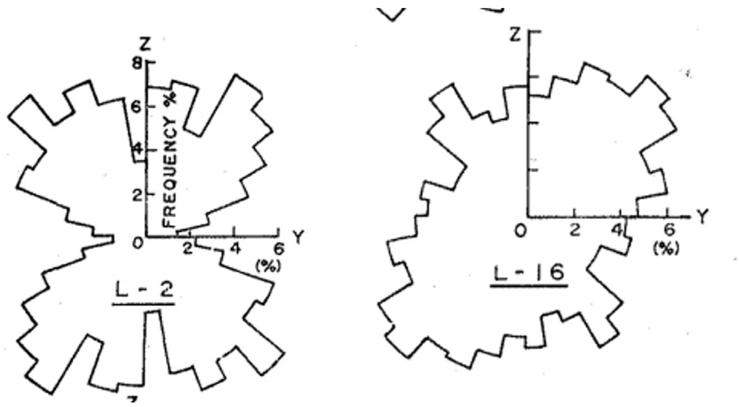

Figure 3: Frequency distribution of contact direction in the vertical plane
(Oda & Konishi, 1974)

Early considerations regarding the physical interpretation of liquids at the atomic level were made. Various models from gas theory and crystal theory (models for solids) were adapted for this purpose. However, due to the absence of long-range order in the molecular structure of fluids, these models yielded results that were not physically meaningful. It turns out that in liquids, only a short-range order exists in the vicinity of the nearest or next-nearest molecule (Bernal, 1959). Bernal described a distribution function to characterize general fluids. The distribution function $g(r)$ represented the probability of finding another molecule at a distance r. The difference from solids is that the molecular structure is subject to constant change due to the weak bonds between the individual molecules.

Derivation of the model of internal structure

Building on the phenomena described above — which arise from the internal structure, whatever its nature, whether due to specific grain contacts within the aggregate or to the exchange of momentum between molecules during relative motion — it is now to develop a model that captures these characteristics and describes them using simple parameters. At the current stage of development, two descriptive parameters are initially used for the model. The first parameter accounts for the geometric factor of contacts or momentum orientation and is referred to as the angle of internal structure ω. A second parameter defines an internal cohesive potential f_t (Figure 4). The basic idea of the model of internal structure is a phenomenological consolidation of the internal factors governing impulse diffusion via the mediating parameter of the angle of internal structure. This parameter represents a state variable of the system and, in simplified terms, describes the systems ability to concentrate loads. In addition, a second variable — the cohesive potential — represents the intrinsic cohesion of the material or system and its ability to maintain stability without external support. Visually, the cohesive potential of the material corresponds to an internal tension spring and could correlate with the elastic potential of the material.

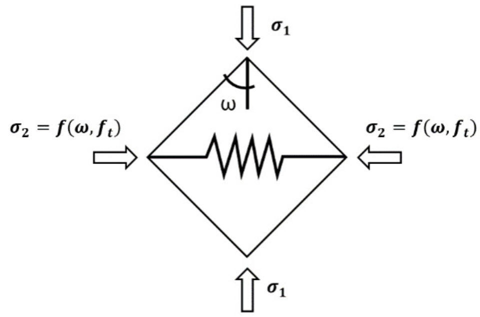

Figure 4: Idealized representation of the model in the plane stress space

To simplify, for example, a maximally possible planar stress state in σ_1 and σ_2 can only be maintained if the supporting stress σ_2 can accommodate the stress propagation from depending on the internal structure and the cohesive potential (Equation (3)).

$$\sigma_1 = (\sigma_2 + f_t) \cdot \cot(\omega) \tag{3}$$

Considering the previous investigations into the quantification of the internal structure, it can be inferred that there may be capacity for structural change, which must naturally be described, at least initially, as material dependent. For example, in an initial increase in the concentration of contact orientations in the vertical direction, i.e., the principal loading direction (Figure 5). This is represented in the model of internal structure by a reduction in the angle of the internal structure ω . On the one hand, this results in a reduction in load propagation and thus a reduction in the necessary support stresses within the structure; on the other hand, it also allows the representation of plastic deformation within the context of classical plasticity theory (Hill, 1998). A change in the structure, at the mesoscopic scale of the granular solid, occurs through relative motion of the grains. In the process, energy is released, among other things, through gran-to-grain friction, which is no longer available to the system as elastic potential. A change in the angle of the internal structure is thus equivalent to energy loss.

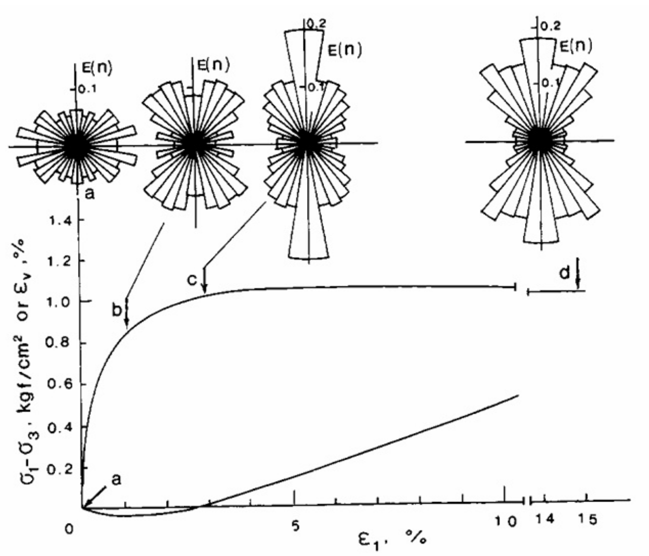

Figure 5: Structural change under triaxial loading
(Oda, 1993)

This interpretation of the internal structure and its capacity for change, in combination with the material's cohesive potential, is the starting point for describing the plastic transition behavior of highly deformable sealing compound materials. It was demonstrated that utilizing the entire deformation range of the diaphragm material beyond the elastic region, up to the uniaxial compressive strength, is justified. This observation is consistent with Kayser's observation of single-phase diaphragm wall mixtures (Kayser, 1995). Internal material redistribution (concentration of the internal structure) upon reaching the material's tensile strength allows the plastic transition zone to be explained beyond the elastic deformation range without the internal tensile stresses exceeding the material's tensile strength or cohesive potential. This rules out the possibility of sustained crack formation in the microstructure (Figure 6: Structural change in the plastic deformation range). As a result, a novel design concept utilizing a reduced material stiffness could be implemented in the current draft of the DWA-M 512-3 standard.

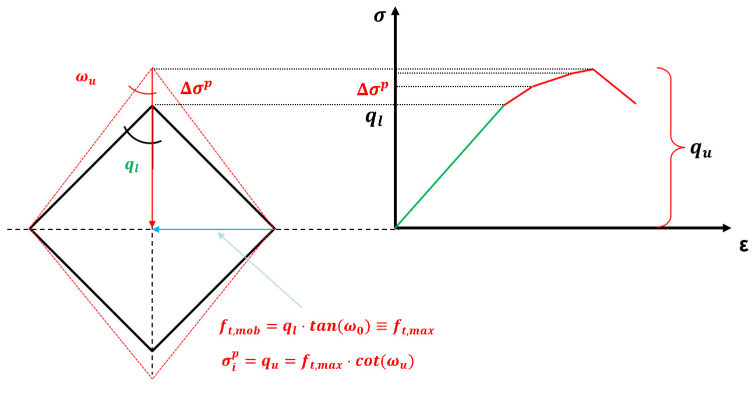

Figure 6: Structural change in the plastic deformation range

Rheological Fundamentals

Rheology is the key discipline for describing the deformation of bodies, whether liquid or solid. For the mathematical description of liquid materials, a categorization according to the underlying parameters is presented in Figure 7. For context, it is necessary to show few basic concepts.

The shear rate or fluid deformation is a quantity derived from the velocity field $\boldsymbol{u}$, which is correlated with the shear stresses in the fluid. To separate pure deformation or change in shape from rotational motions, the symmetric part of the velocity gradient $\nabla\boldsymbol{u}$ is used in the continuum. (Equation (4)):

$$\boldsymbol{D} = \frac{1}{2}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) \tag{4}$$

Furthermore, for most generalized Newtonian fluids, the proportionality between shear stress $\boldsymbol{\tau}$ and the deviatoric component of the deformation (referred to here as the shear rate) is defined according Equation (5):

$$\tau = 2 \cdot \mu \cdot \left(D - \frac{1}{3} \cdot tr(D)\right) \tag{5}$$

When assuming a functional relationship between viscosity and shear rate (for non-Newtonian fluids), a scalar quantity is determined using the Frobenius norm instead of the two-dimensional shear rate tensor (Equation (6))

$$\dot{\gamma} = \sqrt{2} \cdot |D| \tag{6}$$

The proportionality is formed by the initially constant factor μ or η , the dynamic viscosity. Based on the relationship between shear rate and shear stress, different types of material behavior are distinguished at the macroscopic scale (Figure 7). In addition to the viscous stress components described above, which only come into play during a shear rate gradient within the structure, there is also the parameter of the rheological yield stress τ_f. In simple terms, the yield stress or yield point describes the shear stress required to transition the material from a solid state to a state of viscous flow. This enables the CLSM to form a stable suspension.

Description of highly concentrated suspensions

As previously described, highly concentrated suspensions consist of a mixture of dispersed solids and a surrounding liquid phase. For example, according to (*DIN 1045-2*, 2023), normal concrete has a volumetric solid content of approx. 70 Vol.-%, approx. 63 Vol.-% (SCC), and based on experience 53 Vol.-% (CLSM). At the microscopic scale, however the cement paste or the carrier suspension surround the aggregate can already be considered a solid-rich suspension. However, at the mesoscopic scale, within the size range of the aggregate, it behaves as a fluid. In Figure 8, the schematic relationship between the volumetric solid content, relative to the percolation limit ϕ_{max} , and the resulting development of the rheological parameters is shown. Model experiments on the deaeration behavior of highly concentrated suspensions (Sosinka, 2021) illustrate a significant effect that can arise due to the granular structure of highly concentrated suspensions. For instance, the release of air bubbles and the size of the corresponding air bubbles in pure bentonite suspensions and suspensions with relatively low solid content correlate well with the rheological yield point. As the solid saturation of the suspension increased, sustained changes in the microstructure were observed due to the movement of the air bubbles. The result was a local change in the solid concentration and thus in the local rheological properties of the material (Figure 9). This is an effect that is not captured in either the numerical or analytical analysis of the material's behavior.

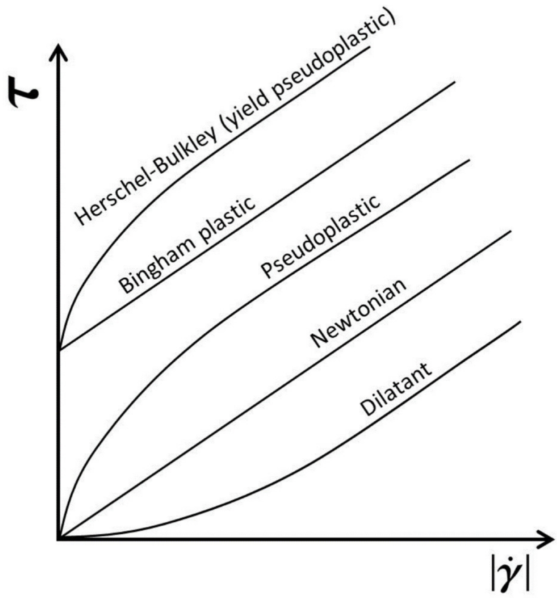

Figure 7: Qualitative behavior of various rheological models. (Mehta et al., 2018)

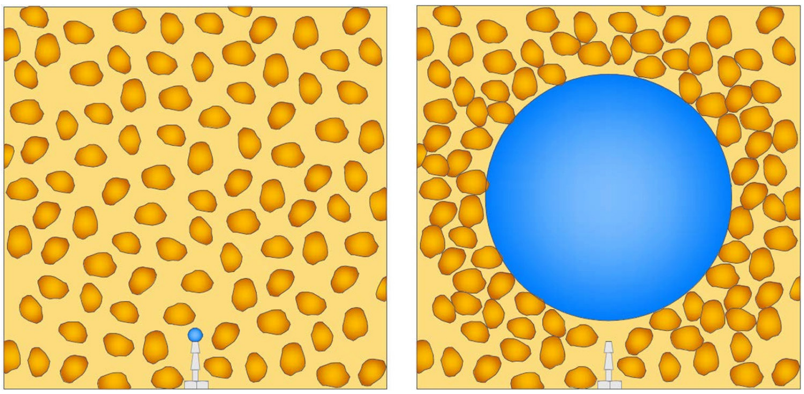

Figure 8: Change in the granular structure of the suspension. (Sosinka, 2021)

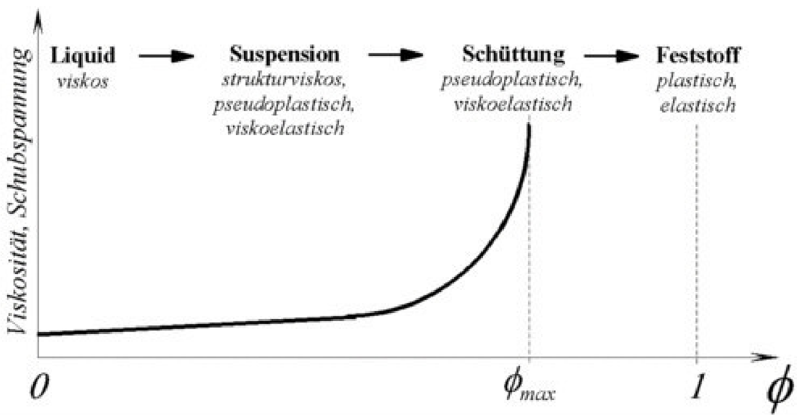

Figure 9: Influence of the volumetric solids content. (Mattke, 2006)

Another challenge arises in the numerical description of solid-rich suspensions in the context of CFD (computational fluid dynamics). The representation of non-Newtonian fluids within continuum mechanics is typically carried out using generalized Newtonian models as described above. The problem can be easily illustrated using the Bingham model, which is the most commonly used model for flowable construction materials; here, the viscosity used in the momentum equation is defined as a function of the shear rate (Equation (6)). When implementing this Bingham model equation numerically, the fluid's viscosities can become virtually infinite as the shear rate approaches the limit of zero. A conventional interpretation therefore employs a biviscous model according to (Tanner & Milhorpe, 1983) by dividing the flow behavior into two regions of different viscosities. Up to a limit value of the shear rate $\dot{\gamma}_{crit}$, the material is assigned a fictitious very high viscosity to simulate a stiff or solid like behavior. As the shear rate transitions $\dot{\gamma} \geq \dot{\gamma}_{crit}$, the viscosity is determined according to equation (7). The complete relationship is shown in equation (8)

$$\eta(\dot{\gamma}) = \frac{\tau_0}{\dot{\gamma}} + \eta_{pl} \cdot \dot{\gamma} \quad (7)$$

$$\eta(\dot{\gamma}) = \min\left(\eta_0, \frac{\tau_0}{\dot{\gamma}} + \eta_{pl} \cdot \dot{\gamma}\right) \quad (8)$$

Although it appears that simulation results based on determined rheological parameters are in good agreement with the vertical flow model according to equation (2), there are significant differences when comparing the simulation (Figure 10) with the real slumb tests in the laboratory. The complex spatial flow system and the resulting structural changes in the granular components of the suspension are considered to be the reason for this.

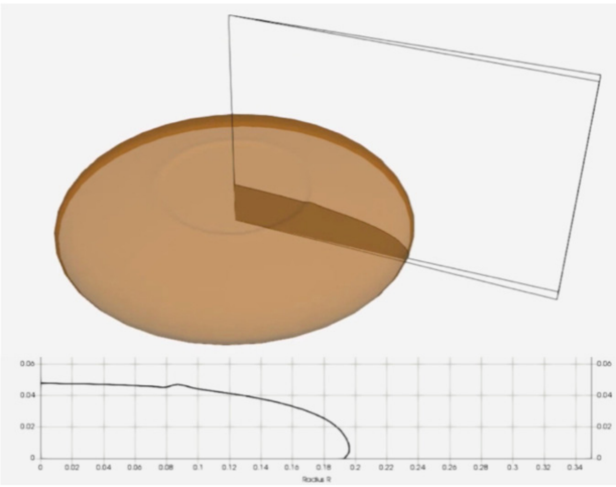

Figure 10: CFD simulation of the slumb test

To approach this, a detailed look at the mathematical formulation of liquid flow is needed. The flow behavior of solids or liquids is generally described by the Navier-Stokes equation in the continuum (simplified for incompressible fluids):

$$\rho \cdot \left(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u}\right) = -\nabla p + \mu \Delta \boldsymbol{u} + \boldsymbol{f} \quad (9)$$

On the left-hand side, the local change and the advection of momentum are shown. On the right-hand side, ∇p denotes the pressure gradient and $\boldsymbol{f}$ involve volume forces such as the gravitational force. Particular attention should be paid to the diffusion term $\mu \Delta \boldsymbol{u}$, as this describes the momentum diffusion. For simple Newtonian fluids, this corresponds to the direct momentum exchange between neighboring molecular layers under relative motion (Chapman & Cowling, 1970; Greenshields & Weller, 2022). Using an analogy to the elastic collision of spheres, the measure of internal structure should also be incorporated into the description of momentum diffusion here.

Oscillatory rheometry has proven to be a promising method for identifying structural change processes in solid-rich suspensions. The basic principle involves exciting the material via a harmonic displacement or force amplitude at a given frequency. The material's response also oscillates and consists of a corresponding amplitude, frequency and phase shift (Figure 11). Two limit values can be defined for the material's response function. If the response is in phase with the deflection, this corresponds to linear elastic material behavior according to Hooke. If a phase shift of $\delta = 90°$ relative to the deflection occurs, the response is consequently in phase with the time derivative of the deflection — the shear rate — and the material exhibits ideal viscous behavior. For phase shifts of $0° < \delta < 90°$, the material exhibits both elastic recovery and viscous energy losses. In addition, Lissajous diagrams are frequently generated from the measured values. Figure 12 shows characteristic Lissajous diagrams from an oscillation test using an amplitude sweep. A solid-rich bentonite-sand suspension was investigated with a volumetric solids content of approx. 51 Vol.-% and a grain size distribution of 0.1 – 1 mm. At low amplitude of deflection, the material exhibits an elliptical force-displacement relationship. This suggests that viscous friction losses occur within the material; the area enclosed by the ellipse corresponds to the energy loss. As the amplitude is further increased, plastic structural changes occur in the material, as illustrated by the nonlinear progression of the Lissajous diagram in Figure 12 (right). As the deflection increases, the granular structure within the material becomes increasingly compacted, as in the deaeration experiments (Sosinka, 2021), local concentrations of solids form, leading to a higher degree of branching in the force network within the grain structure. At a deflection of approximately 0,5°, the measuring body thus encounters stiffer material with higher momentum and force diffusion, which is represented by the steeper rise in the force-displacement-curve. The structural transformation was also demonstrated using rotational rheometry. In this method, the material was sheared continuously through the measuring body (vane cell). In the plots from Figure 13, it is clearly evident that for the suspension with lower solid content (top), no significant change in the material's resistance can be detected during the entire shearing process. In contrast, in the material with a higher solids content (bottom), it is visible that after an initially stronger resistance to shearing — due, for example, to the mobilization and orientation of specific contact networks — the resistance drops to a constant residual value. This can be explained by the fact that, along the shear path, the structure changes in such a way that the granular solids move away from the shear gap to certain extent and can therefore no longer be mobilized to contribute to the resistance.

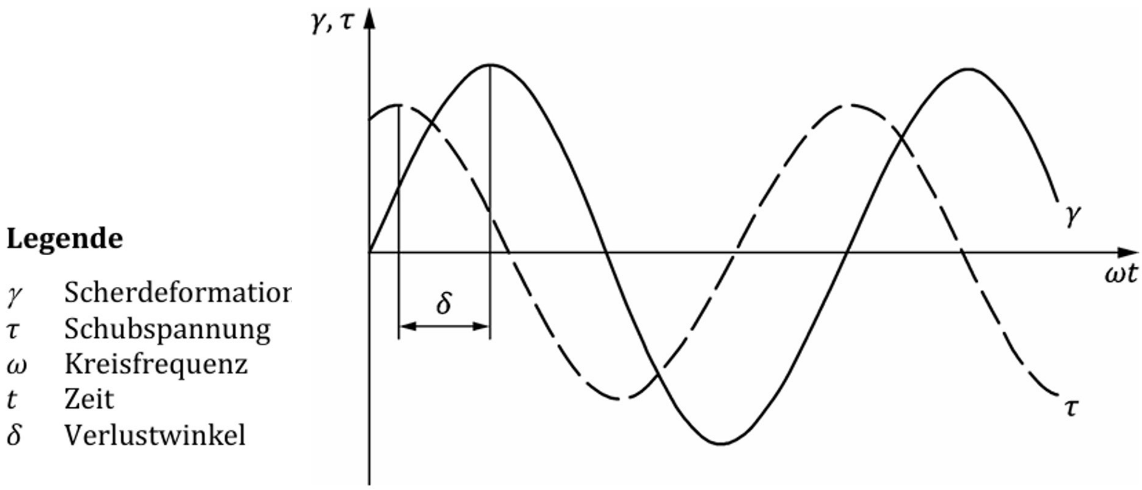

Figure 11: Oscillatory rheometry. (DIN EN ISO 12345)

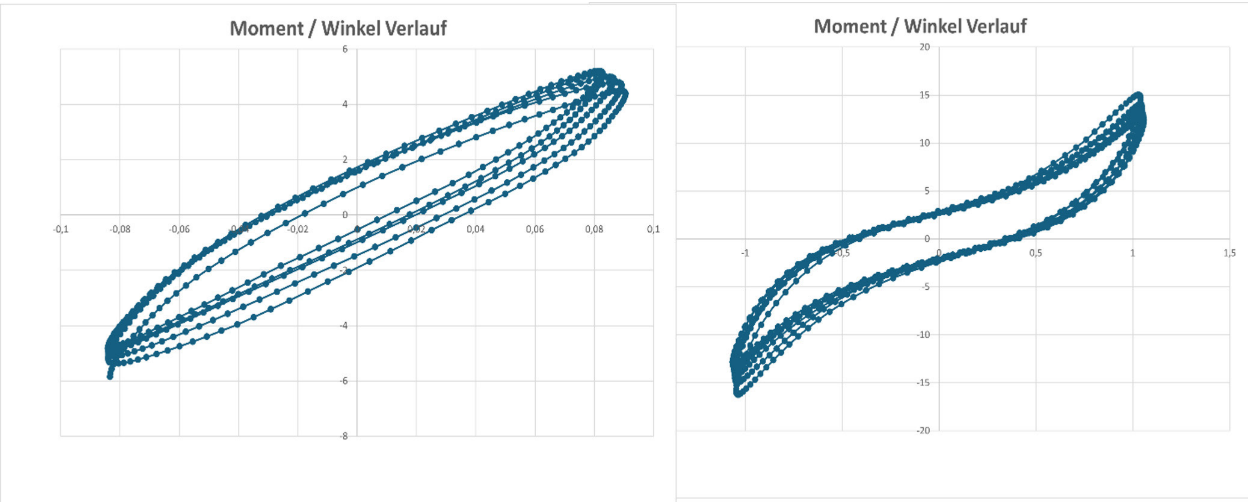

Figure 12: Lissajous figure after amplitude sweep, left at an amplitude of 0,2°, right at an amplitude of 1,0°. Constant frequency of 0,1 Hz

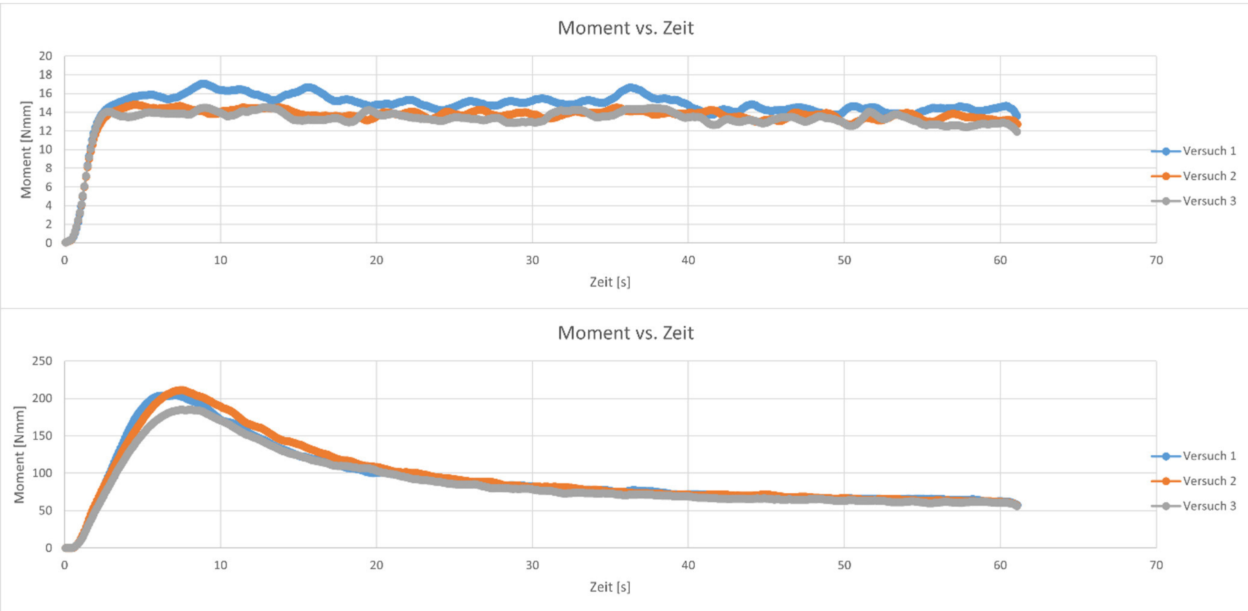

Figure 13: Results of rotational rheometric analysis of materials with diffrent solid concentrations. Top: 36 Vol.-%, bottom 49 Vol.-%

Conclusion and Outlook

Current considerations indicate that the complex behavior of solid-rich suspensions can be phenomenologically explained using the model of internal structure. Based on the findings, the next step will be to derive a measure of structural transformation and the underlying parameters e.g., the spatial stress state of the fluid. The goal is to reduce the discrepancy that arises when modeling non-Newtonian material laws. For the concrete formulation of momentum diffusion, various granulometric parameters, such as the particle size distribution, will be incorporated in combination with statistical descriptions — for example, regarding contact probability — as a measure of the structure that builds up and is represented by the angle of internal structure ω .

Furthermore, the model of internal structure is already incorporated into the description of solids in uniaxial compression tests (Ramler-Kowollik & Quarg-Vonscheidt, 2024). In addition, a team at the Koblenz University of Applied Sciences is working to describe the material behavior of cold asphalt and BSM (bitumen stabilized material) on the fundamental principles of the model.

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