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Invited Review

Rheological properties of a multiscale granular system during mixing of cemented paste backfill: A review

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Abstract: The technology of cemented paste backfill (CPB) is an effective method for green mining. In CPB, mixing is a vital process aiming to prepare a paste that meets the non-stratification, non-segregation, and non-bleeding requirements. As a multiscale granular system, homogenization is one of the challenges in the paste-mixing process. Due to the high shearing, high concentration, and multiscale characteristics, paste exhibits complex rheological properties in the mixing process. An overview of the mesomechanics and structural evolution is presented in this review. The effects of various influencing factors on the paste's rheological properties were investigated, and the rheological models of the paste were outlined from the macroscopic and mesoscopic levels. The results show that the mechanical effects and structural evolution are the fundamental factors affecting the rheological properties of the paste. Existing problems and future development trends are presented to change the practice where the CPB process comes first and the theory lags.

Keywords: cemented paste backfill; rheology; mixing process; mesomechanics; structural evolution

1. Introduction

The development and production of metallic mineral resources have resulted in many solid wastes and mining areas. Based on statistics, the solid waste stock is approximately 70 billion tons, and underground mining goaves account for 1.28 billion cubic meters in China [1–2]. Solid wastes stacked on surfaces occupy a large amount of land and pose a severe environmental threat. There is a high risk of dam breaks in tailings ponds, landslides in waste rock fields, and numerous collapse accidents in goaves. Solid wastes and goaves are two primary sources of pollution and hazards from metal mines. The best approach is to fill the goaves with solid wastes from mines [3–4]. As a new stage in the development of filling technology, the process of cemented paste backfill (CPB) involves preparing solid mine wastes into a high-concentration slurry that meets the non-stratification, non-segregation, and non-bleeding requirements and then piping to a goaf [5]. The CPB technology can optimize solid waste resource utilization and source reduction, promote a coordinated solution to solid waste pollution and disaster prevention, and become a goal-oriented, green, efficient, and safe production in mines [6].

With the ascendant and rapid advancement, the CPB technology is being developed, which has been widely adopted in more than 200 metal mines in China, proving it to be economically beneficial [7]. However, in practice, filling materials, such as tailings, aggregates, and binders, in the mixing process are not evenly mixed. As a result, the paste cannot meet the non-stratification, non-segregation, and non-bleeding requirements, leading to pipe blocking in the transportation process and uneven strength of the stope-filling body [8]. The problem is mainly because engineering practices far exceed fundamental knowledge, and there is inadequate theoretical research on complex particle transportation during mixing. Hence, it is critical to investigate the dispersion of materials.

The effect of paste mixing is affected by the particle scale, concentration, and shearing effect. The composition of paste spans more than six orders of magnitude, coarse aggregates can reach the centimeter level, and tailings can be even smaller than 100 nm [9]. Meanwhile, the characteristic of being more solid than liquid results in the paste with high viscosity. The high concentration and multiscale features of paste cause complex changes in the rheological properties [10]. Another critical influence factor is the mixing condition. Continuous shearing changes the mesostructure of the paste, which directly affects the macroscopic rheological properties [11]. The aggregation, breakage, and dispersion of particles during the mixing process are governed by interparticle interactions [12–13]. Therefore, the rheological properties of paste are primarily determined by the mesomechanics and internal

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structure [14–15]. However, most previous studies focused on the mixing method, material dispersion simulation, and macroscopic evaluation of homogenization effects, lacking an understanding of the mesomechanics and mesostructure of the paste [16–17]. Consequently, clarifying the correlation among the mesomechanics, structure evolution, and rheology of the paste during the mixing process is essential.

Based on the macroscale and mesoscale rheological models of the paste, this paper reviews the research process of paste mixing. In view of the paste's multiscale and high concentration characteristics, this paper is dedicated to studying the rheological properties of multiscale granular systems under shearing. It also presents a summary to clarify the mechanical interactions and structure evolution that governs the rheology of the paste. In this article, we hope to provide new insights into the effects of mesomechanics and structural evolution on the rheological properties of paste, intending to achieve a precise paste preparation.

2. Mesomechanics mechanism of multiscale granular systems

In the mixing process, particles are in full contact with water and are connected by liquid, resulting in a meso-heterogeneous state of paste. Continuous shearing changes the multiscale granular system from the heterogeneous state to the homogeneous state, the connection between particles is destroyed, and particles are fully dispersed. Based on the particle distribution state, the mixing process in the multiscale granular system is divided into the pre-stage and while-stage, and the mechanical mechanisms of the two stages are quite different [18].

2.1. Mesomechanics mechanism in the pre-stage

The shearing force promotes the liquid to wet the particles in the pre-stage of mixing. When the wet particles are close, the liquid forms a liquid bridge at the contact point and the nearby area so that the particles are connected, and a liquid bridge force exists between the particles. The liquid bridge force consists of a static liquid bridge force and a dynamic liquid bridge force. The dynamic liquid bridge force is generally more prominent than the static liquid bridge force [19]. Capillary, viscous, and friction forces control the liquid bridge force [20]. The capillary force is the resultant force of the liquid surface tension and hydrostatic pressure. The viscous force originates from the liquid between particles, and the accumulation of particles generates friction. The capillary force promotes particle aggregation, and the viscous force and friction help particles to disperse. The water content of the paste is the main factor leading to the change in the force between particles [21]. The capillary force reaches the maximum and decreases with the increase in the water content [22]. Correspondingly, when the liquid saturation ratio comes to approximately 20vol%, the liquid bridge force reaches its maximum and then decreases [23].

Studies on the mesomechanics of the pre-stage are generally conducted with research knowledge on related fields, such as wet granulation and concrete rheology. By contrast, studies on paste mixing are described qualitatively. Meanwhile, capillary, viscous, and frictional forces continuously act on particles at all scales. Hence, more research is needed to quantify the effects of mesomechanical interactions during the pre-stage.

2.2. Mesomechanics mechanism in the while-stage

Due to the extensiveness of the particle size in multiscale granular systems, forces between particles are complex and variable in the while-stage of mixing [24]. Mechanical interactions between particles depend on particle gradation. The multiscale granular system is divided into a colloidal and a non-colloidal granular system based on the particle size of the composition. There are different interparticle forces for different granular systems.

In the colloidal granular system, Brownian, van der Waals, electrostatic repulsion, hydration, hydrodynamic, and friction forces dominate the mechanical interaction between particles. Driven by the temperature gradients, Brownian forces are generated that promote particle diffusion [25]. Several forces affect particle interactions with particle sizes larger than the range of the Brownian force, including van der Waals, electrostatic, hydration, hydrodynamic, and friction forces [26–27]. The granular system exhibits differences in interparticle forces depending on the concentration and shearing conditions. The hydrodynamic force dominates the colloidal system of medium-concentration slurries, whereas the friction force dominates the system of high-concentration slurries [28]. The electrostatic force prevents particles from contacting one another at low shear rates, whereas the hydrodynamic force promotes particle aggregation at high shear rates [29–30].

In the non-colloidal granular system, the motion of particles is controlled by the hydrodynamic and frictional forces. The hydrodynamic force has a great effect on particles larger than 10 μm [31]. The friction force is generated by direct contact between particles depending on two parameters, i.e., the distance between particles and particle roughness [32]. The particle roughness increases the apparent radius of particles, increasing the density of the frictional contact network. As the distance between particles is less than or equal to the particle roughness, friction occurs between particles [33–34]. Particles tend to rearrange, and the slurry transitions from frictionless to friction-dominated states [35]. The concentration significantly affects the interparticle forces, with the hydrodynamic force dominating between aggregates–particles and aggregates–mortar in low-concentration slurries and the frictional force dominating between aggregates in high-concentration slurries [36–37]. The dominant force in a multiscale granular system can be determined by dimensionless numbers, such as the Péclet number (used to evaluate the relative magnitude between the hydrodynamic force and Brownian force), Γ number (generally used to compare the effects of the hydrodynamic force and colloidal force on particle interactions), and Ba number (a modified Bagnold's number, which can be used to estimate the effect of the inertial force and viscous force) [38].

The schematic diagram of the mesomechanics of the multiscale granular system during the mixing process is shown in Fig. 1. The mesomechanics differ in the pre-stage and while-stage mixing. The capillary force, viscous force, and friction dominate the interparticle forces in the pre-stage. The Brownian force, electrostatic force, van der Waals force, hydrodynamic force, and friction influence the while-stage mesoscopic behavior. Combining the study of the interaction force between particles with the analysis of the influencing factors is necessary. The interparticle mechanics research, however, emphasizes the effects of colloidal particles on the rheological properties of paste and less on the influence of non-colloidal particles. To fully explore the mesomechanics mechanism, colloidal and non-colloidal particles must be considered together.

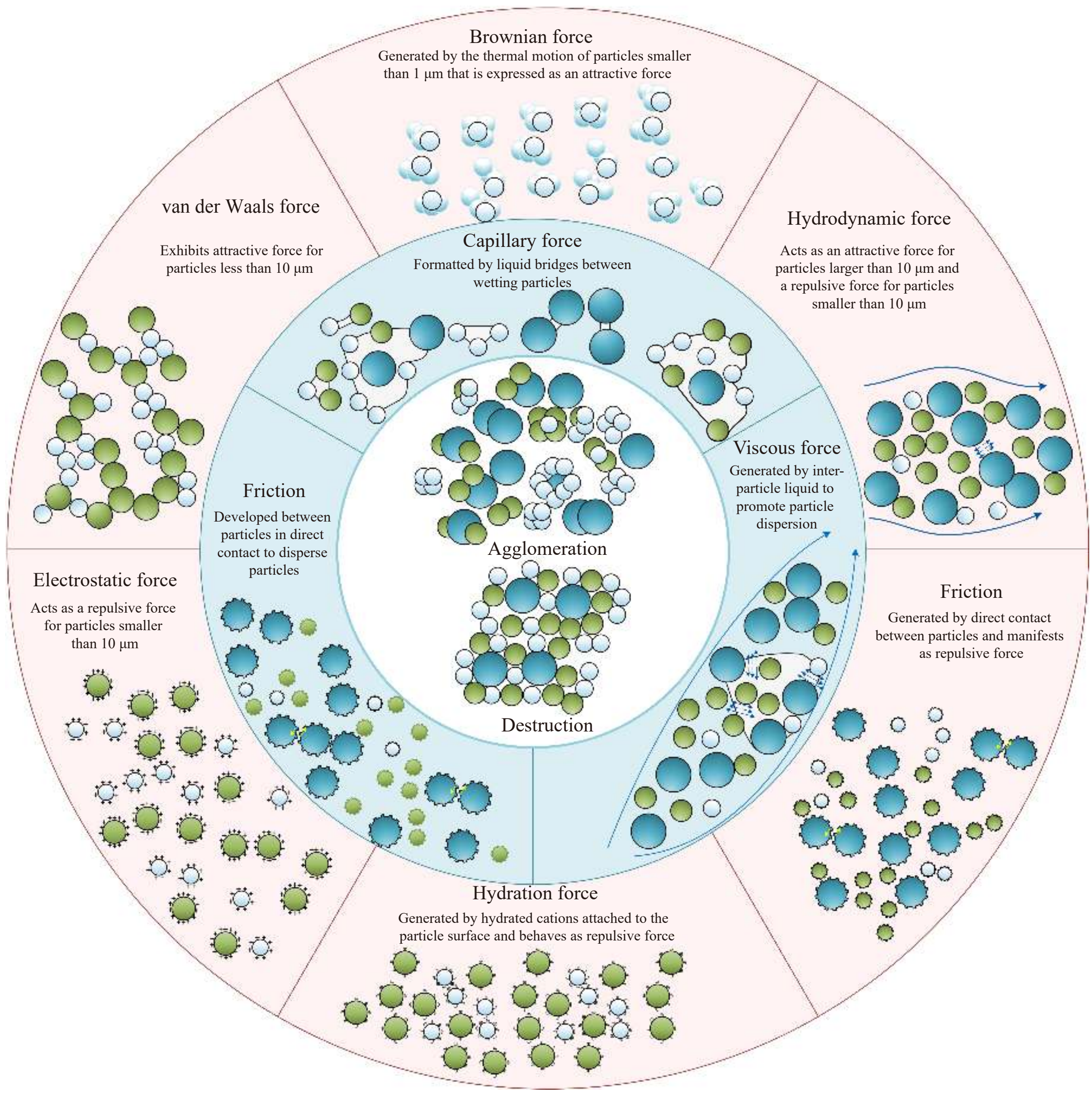

Fig. 1. Mesomechanics during the pre-stage and while-stage mixing.

3. Structural evolution of multiscale granular systems

Particles migrate due to the shearing force and interparticle force, and the mesostructure of the multiscale particle system continues to evolve. There is a difference in the mechanical causes of the structural evolution at pre- and while-stage mixing. That is, the capillary force connects the particles through the liquid bridge to form clusters [39]. The friction force, viscous force, and shearing force prevent the particles from agglomerating at the pre-stage mixing. At the while-stage mixing, the Brownian force and van der Waals force agglomerate the particles into clusters. The shearing force combined with the electrostatic repulsion, hydrodynamic force, and friction force promotes the dispersion of clusters [40].

3.1. Structural evolution in the pre-stage

In the pre-stage of mixing, the dry particles are agglomerated into clusters in contact with water. The formation of agglomerates in the pre-stage is shown in Fig. 2 [41]. As the liquid content of the system increases, the clusters gradually shift from the pendular state and funicular state to the capillary state. The water content of the clusters varied in different states. A liquid bridge connects the particles at the contact point in the pendular state. In the funicular state, the clusters are not completely wet, while in the capillary state, all gaps in the clusters are filled with liquid [42]. The high liquid content enables the particle clusters to connect and form agglomerates until the end of the pre-stage mixing, when the paste behaves like a "raspberry-like" shape [43]. Liquid bridges connect particles to form the network in the multiscale granular system. As the water content of the granular system increases, the shortest distance required for the liquid bridge to break increases, and the strength of the network structure decreases as the distance between particles increases [44]. In the field of wet granulation, the water content of liquid bridges at different states is different. The maximum moisture content of liquid bridges in the pendular state is approximately 13vol%, and the moisture content of liquid bridges in the funicular state is 13vol%–25vol% [45]. Due to the difference in the particle size and gradation of materials, the moisture content of paste is more complicated than that in wet granulation, so the effect of capillary force on the mesostructure should be analyzed deeply.

The agglomerates are destroyed before dispersion [46]. Agglomerate breakage has two mechanisms: one is surface erosion that generates small particles without overall damage to the agglomerate, and the other is large-scale fragmentation caused by tensile stress, which leads to the cleavage of the agglomerate into two similar-size clusters [47–48]. Continuous shearing simultaneously induces aggregation, breakage, and dispersion, jointly determined by the liquid surface tension, moisture degree of the particle surface, particle size, and particle shape. The agglomeration and destruction of particles maintain a dynamic equilibrium at the end of the pre-stage of mixing [49].

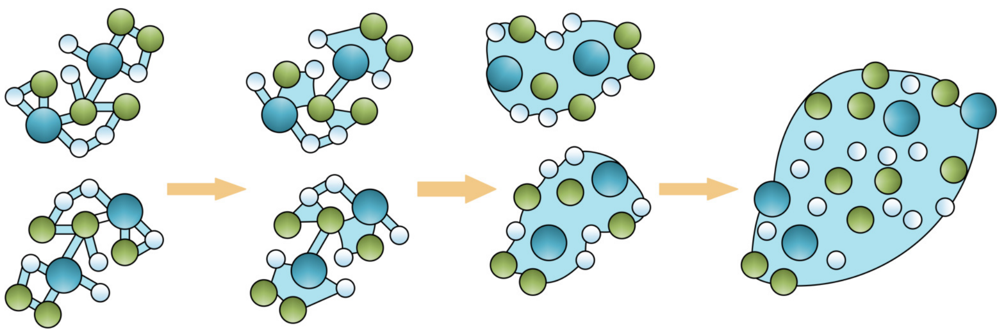

Fig. 2. Formation of agglomerates in the pre-stage [41]. Modified from *Powder Technol.*, 117, S.M. Iveson, J.D. Litster, K. Hapgood, and B.J. Ennis, Nucleation, growth and breakage phenomena in agitated wet granulation processes: A review, 3–39, Copyright 2001, with permission from Elsevier.

3.2. Structural evolution in the while-stage

In the while-stage, the multiscale granular system is transformed from the meso-heterogeneous slurry to the homogeneous paste. Multiscale particles agglomerate and destroy, and reversible and irreversible agglomerates exist at this stage. Reversible aggregation forms from perikinetic aggregation, orthokinetic aggregation, and differential sedimentation. Perikinetic aggregation is promoted by the Brownian force, the shearing force induces the orthokinetic aggregation of particles, and differential sedimentation is caused by the difference in the particle settling velocity [50]. Irreversible agglomerates form from the binder hydration, which is encapsulated in a hydrate film. Reversible agglomerates may recover after the clusters and agglomerates are destroyed by shearing. However, irreversible agglomerates cannot recover to the original state, with a new hydrate film forming around the released binder particles [51].

Studies on the structure evolution in concrete preparation have shown that fine particles agglomerate, nucleate, and grow under continuous shearing [52]. Aggregates are mostly wetted, some wrapped in fine particles simultaneously. Afterward, the agglomerates are destroyed, and a slurry with a uniform distribution of multiscale particles is formed [53]. Paste and concrete are multiscale granular systems, but the existing forms and mesoscopic structures of the materials are different. Paste comprises binders, aggregates, and slurries that have formed a network structure by tailings. Concrete is composed of water, binders, sand, and aggregates.

The mechanism of the mesostructure evolution of the multiscale granular system during mixing is shown in Fig. 3. A significant difficulty in the current research on the evolution process of multiscale granular systems is that most choose to use macroscopic parameters to analyze the structural evolution qualitatively or only quantitatively analyze the mesostructure at different times. The information on the structural evolution during mixing cannot be provided, and the theoretical model of structure destruction and generation in the multiscale granular system has not been developed.

4. Influencing factors of paste rheological properties

In the mixing process, paste has high shearing, high con-

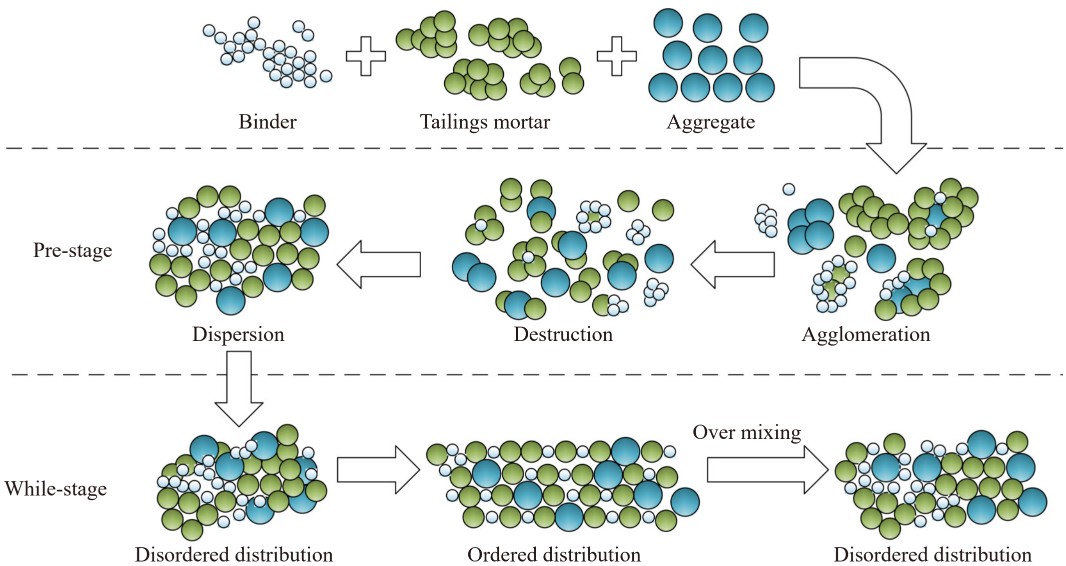

Fig. 3. Mesostructure evolution of multiscale granular systems during mixing.

centration, and multiscale characteristics. Shearing promotes collision between particles, and the concentration and multiscale affect particle packing. The mesomechanics and structure evolution affect the paste rheology.

4.1. Shearing

One of the factors that affect the paste's rheological properties is shearing [54]. As the shear rate increases, the electric double layer of particle diffusion decreases in cement-based paste, and large-size agglomerates are formed by the particles [55]. A high-concentration slurry exhibits a shear thickening behavior under a high shear rate [30]. Based on the structural evolution of colloidal suspensions and paste characteristics, the rheological properties of paste can be categorized into equilibrium, shear thinning, and shear thickening stages, as shown in Fig. 4 [56].

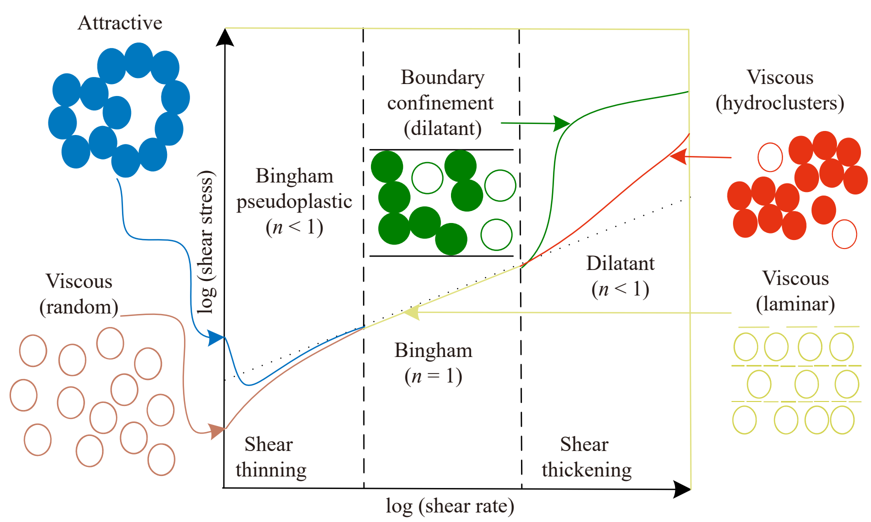

Fig. 4. Mesoscopic evolution and rheological properties of a paste under shearing. Modified from E. Brown and H.M. Jaeger, *Science*, 333, 1230-1231 (2011) [56]. Reprinted with permission from AAAS.

The slurry behaves as shear thinning as the shear rate is lower than the first threshold. The fluidity of the paste is better as the shear rate is between the first and second thresholds. When the shear rate exceeds the second threshold, the double layer structure collapses, and the ions and early hydrates dissolve in water. The rheological properties of the paste are similar to shear thickening. However, several studies have concluded that the mesostructure cannot recover, and the paste is a pseudo-shear thickening slurry [57–58].

Due to the high concentration and multiscale characteristics of the paste, it takes longer to reach the homogeneous state. Based on studies on cement-based slurries, binders undergo a hydration reaction with water, and the short mixing time efficiently induces the uneven dispersion of the binder [59]. Increasing the mixing time can effectively reduce the size of agglomerates in the cement-based slurry and promote the hydration reaction [60]. Appropriate mixing time is sufficient to ensure the lowest apparent viscosity of paste, whereas excessive mixing reduces the fluidity of the paste and the CPB body strength [61].

4.2. Concentration

Concentration (including the volume fraction, which is the ratio of the solid volume to the slurry volume, and the mass fraction, which is the ratio of the solid mass to the slurry mass) affects the paste mesostructure. The critical volume fraction φ_c and maximum volume fraction φ_m characterize the packing state of particles [62], as shown in Fig. 5 [24]. When the volume fraction is less than φ_c, the colloidal force dominates between particles. The particles begin to contact, the continuous rigid particle network is formed as the volume fraction is greater than φ_c, the friction controls the flow behavior of the slurry, and the colloidal force has little effect on the mesostructure. Under a high volume fraction, the repulsive force between particles cannot gradually bear the normal force, and the direct contact area of particles increases. When the volume fraction approaches φ_m, the particles are connected by solid-like substances [63].

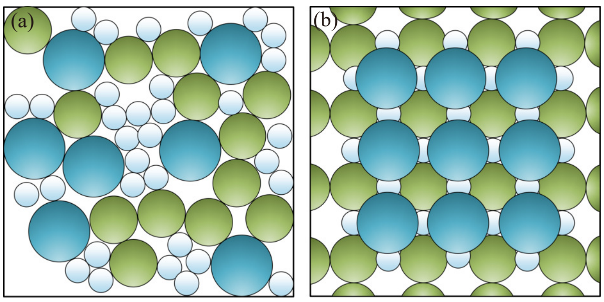

Fig. 5. Packing state of particles: (a) critical concentration and (b) maximum concentration [24]. Modified from *Cem. Concr. Res.*, 40, B.D. N. Roussel, A. Lemaître, R.J. Flatt, and P. Coussot, Steady state flow of cement suspensions: A micromechanical state of the art, 77-84, Copyright 2010, with permission from Elsevier.

The effect of the mass fraction on the rheological properties of paste is reflected in that a low mass fraction results in a high porosity. By contrast, a high mass fraction results in a high viscosity [64]. Homogenization is hard at a high mass fraction of paste. As the slurry mass fraction is greater than the critical mass fraction, the water content is too low, which is not conducive to the hydration reaction of the binder. The paste yield stress and dynamic viscosity exponentially increase with the increase in the mass fraction, and the fluidity worsens [65]. A mass fraction of paste between 75% and 85% is required for CPB technology.

4.3. Particle scale

The particle scale affects the rheological properties of the paste. A paste is composed of fine particles and aggregates, and the fine particles contain tailings and binders [66]. The particle size of tailings is classified into three categories: sand, mud, and clay. Cement is generally used as the binder; ground blast furnace slag and phosphogypsum can also be utilized [67–68]. Aggregates are usually derived from the waste rock generated in the mining process and the slag in the smelting process. According to the technical specification for unclassified tailing paste, the particle size of coarse aggregates is 4.75–20 mm, and the particle size of fine aggregates is 0.075–4.75 mm [69]. The effects of fine particles and aggregates on the rheological properties of the paste are significantly different [70].

Tailings and binders affect the rheological properties of paste in terms of particle size composition, particle shape, and chemical reaction [71]. The tailings lubricate and prevent aggregates from settling [72]. To ensure the transportation process, the mass fraction of tailings less than 20 μm in the paste should be greater than 15% [73]. The particle shape has a great impact on the fluidity of the paste, especially for the paste with high aspect ratio particles [74]. There are two theories on the binder on rheological properties of paste: One theory holds that the binder alters the paste's gradation distribution, and at an appropriate amount of the binder, the paste's viscosity and yield stress decrease [75]. Another theory holds that hydrates cannot be discounted, and there is a network structure composed of hydrates in the paste [76].

Another vital component of paste is aggregates. The structural effect caused by aggregates cannot be ignored [77]. A high aggregate content leads to the loosening effect [62]. A sufficient fine particle content efficiently induces the wall effect, whereas the wedging effect occurs as there are insufficient or too many particles to fill the inter-aggregate voids. The particle packing density decreases by the structural effects, and the optimal aggregate content can be found in multiscale granular systems [78]. The rheological properties of the paste need to be comprehensively considered in terms of the aggregate content, shape, and gradation [79–80]. In the case of high aggregate contents, the large-sphericity aggregate is highly conducive to the paste flow [81]. Under a low aggregate content, the plastic viscosity of a slurry is reduced [82]. However, increasing the content of large-sized aggregates can also easily raise the possibility of pipe plugging and stratification of the filling body [83]. The particle size distribution and maximum particle size of the aggregate play a significant role in the rheological properties of the paste. The greater the maximum particle size, the lower the rheological parameters of the paste [84]. Meanwhile, if the particle size distribution of aggregates is overly fine or coarse, the micropores and cracks increase, and thus the strength of the filling body decreases. Therefore, optimizing the particle size distribution of the coarse particles is essential to ensure the paste's fluidity and backfill strength [85–86].

In summary, the shearing effect, concentration, and particle scale jointly determine the rheological properties of paste, shearing induces multiscale particle migration, and the determination of shearing conditions needs to combine the concentration and gradation distribution. Various influencing factors must be comprehensively considered in the mixing process, and the multi-factor optimization design can achieve the goal of preparing the homogeneous paste.

5. Macroscale and mesoscale rheological models of paste

The shearing effect, concentration, and particle size substantially impact the interaction between particles and the mesostructure, which in turn affects the paste rheology. The rheological model, including the macroscopic and mesoscopic rheological models, can predict the rheological properties of the paste [87]. In the macro-rheological model, macro-parameters are considered to predict the granular system's rheological properties. By contrast, the meso-rheological model quantifies the rheology from the perspective of mesomechanics and structural evolution [88].

5.1. Macroscopic rheological model of paste

Paste exhibits non-Newtonian fluid properties, and the viscosity and yield stress are two characteristic parameters that quantify the rheological properties of a multiscale granular system. Viscosity is affected by the interparticle force, and increasing the spacing or reducing the particle surface contact can reduce friction and thus reduce viscosity [89]. Thixotropy is manifested in the reduction of viscosity under shearing and the gradual recovery of viscosity under static conditions. The yield stress is the minimum stress at which the slurry begins to flow. As the shear stress is smaller than the yield stress, the paste resembles an elastic solid. When the shear stress is greater than the yield stress, the slurry begins to flow viscously. The static and dynamic yield stress can characterize the paste rheology. The static yield stress is the stress required to initiate the slurry flow, and the dynamic yield stress is the minimum stress to maintain the flow of the slurry, which corresponds to the shear stress at the shear rate of zero in the equilibrium flow curve [90].

The macroscopic rheological model assumes that the paste is an ideal homogeneous non-Newtonian fluid. Typical macro-rheological models include Bingham, Herschel–Bulkley (H–B), and Casson models. The macro-rheological model holds the view that the solid–fluid transition stage is continuous, but the paste is in a coexistence state of solid and liquid during the transition stage, and the macro-rheological model cannot explain the paste yielding. In addition, the yield stress obtained by the fitting of the macro-rheological model is high, and generally, the higher the slurry solid concentration, the worse the fitting [91]. The modified Bingham and H–B models can describe the shear thickening behavior, avoiding the negative yield stress [92].

Considering the influence of the physical properties of tailings on the rheological properties, the macro-rheological model of the paste can introduce the stability coefficient as an index to analyze the effect of the particle size distribution on the rheological parameters. The yield stress exponentially increases with the increase in the stability coefficient [93]. The rheological model of uncemented thickened tailings (UTTs), combined with parameters such as true solid density, bulk density, and solid concentration, can characterize the rheological properties. The yield stress of UTTs increases with the true solid density and solid concentration and decreases with the bulk density [94].

Machine learning methods for predicting paste properties have been proven to be effective. Due to the rapid growth of machine learning theory, machine learning models can be used to estimate rheological properties. Based on least-squares support vector machines and particle swarm optimization methods, the model can be established to predict the interface yield stress and plastic viscosity of concrete [95]. A prediction model applied to the sparrow search algorithm to optimize the relevance vector machine has high accuracy in predicting the yield stress of the paste [96].

The macroscopic rheological model is a phenomenological model that can describe the rheological properties of the paste under specific conditions but has limitations in characterizing the phenomena during the solid–fluid transition stage. Predicting the rheological properties of paste through machine learning is a developing method. Nonetheless, such models mainly rely on a large amount of reliable data and relatively good learning models, and machine learning models need to be further developed. The mesoscopic properties essentially determine the macroscopic rheological properties of paste, and the rheological model needs to be extended toward essence. Hence, studying the rheological properties in combination with mesomechanics and structural evolution is necessary.

5.2. Mesoscopic rheological model of paste

The mesoscopic rheological model can be divided into two categories in the slurry: the indirect structural model, which describes the mesostructure by structural parameters, and the direct structural model, which is used to describe the change of agglomerates by the bonds connecting the particles [88].

The indirect structural model simplifies the mesostructure to a structure factor λ [97]. Combining structural dynamics with macro-rheological models, indirect structural models provide a possibility for studying thixotropy [98–99]. Meanwhile, the indirect structural model is suitable for describing the instantaneous transition of slurries from a solid to a fluid state. For the shear localization problem, it can judge whether the fluid is in a steady state [71]. Indirect structural models are suitable for paste and can predict the rheological properties of highly concentrated paste. Combining the constitutive equation and structural evolution equation, an eight-parameter paste rheological model can quantitatively describe the thixotropic behavior of the paste [100].

By contrast, based on the number of particle bonds, the direct structural model combines the force balance analysis of a pair of particles with the volume fraction, gradation distribution, maximum accumulation, percolation threshold, and other parameters to develop the Yodel model, which can be constructed to accurately predict the yield stress of submicron particle slurries [101]. However, the establishment of the Yodel model lies in the ideal assumption that a linear relationship exists between the maximum coordination number of particles and the volume fraction. Based on the discrete element method and Derjaguin–Landau–Verwey–Overbeek theory, the results of the modified Yodel model show good consistency with the experiment results [102]. The mesoscopic rheological model is shown in Table 1.

The macroscopic rheological model can describe the rheological properties of the paste in a steady flow. Nonetheless, there are limitations in characterizing the rheological properties of the paste in the mixing process. The paste rheology is closely related to mesoscopic properties. Therefore, it is necessary to construct a rheological model suitable for paste from the aspects of the interparticle force and structural evolution.

Table 1. Mesoscopic rheological model

Model	Equation	Variables
Toorman [98]	$\tau = (\lambda_0 + \lambda - \lambda_e(\dot{\gamma}))\tau_0 + (\mu_\infty + c\lambda)\dot{\gamma}$	τ—shear stress, λ_0—the maximum value of the structural parameter, λ—structural parameter, λ_e—equilibrium value of the structural parameter, $\dot{\gamma}$—shear rate, τ_0—initial yield stress, μ_∞—Bingham viscosity, c—the difference between the Bingham viscosity and the initial differential viscosity
Roussel [99]	$\tau = (1+\lambda)\tau_0 + k\dot{\gamma}^n,\ \frac{\partial\lambda}{\partial t} = \frac{1}{T\lambda^m} - \alpha\lambda\dot{\gamma}$	τ—shear stress, τ_0—initial yield stress, $\dot{\gamma}$—shear rate, λ—flocculation state, T, m, α—thixotropy parameters, k—consistency coefficient, n—flow index
Coussot *et al.* [103]	$\tau = \eta_0(1+\lambda^n)\dot{\gamma},\ \frac{\mathrm{d}\lambda}{\mathrm{d}t} = \frac{1}{\theta} - \alpha\lambda\dot{\gamma}$	τ—shear stress, $\dot{\gamma}$—shear rate, λ—structural parameter, n—constant positive parameter, η_0—viscosity at an infinite shear rate, $1/\theta$—characteristic time of the build-up structure, α—dimensionless parameter
Møller *et al.* [104]	$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = 0 \Rightarrow \frac{1}{\zeta} = \alpha\lambda_{ss}\dot{\gamma} \Rightarrow \lambda_{ss} = \frac{1}{\alpha\zeta\dot{\gamma}}$, $\sigma_{ss}(\dot{\gamma}) = \dot{\gamma}\eta_0\cdot(1+\beta\cdot(\alpha\zeta\dot{\gamma})^{-n})$, $\sigma_{ss}(\dot{\gamma}) = \dot{\gamma}\eta_0$ (for high shear rate)	λ—structural parameter, ζ—characteristic time of the build-up structure at rest, λ_{ss}—structural parameter at the steady state, $\dot{\gamma}$—shear rate, σ_{ss}—shear stress at the steady state, η_0—limiting viscosity at high shear rates, α, β, and n—parameters that should be specific for a given material
Yang *et al.* [71]	$\tau = \left(1+\beta_0 e^{-\xi\gamma t}\right)\tau_0 + \mu\gamma^n$	τ—shear stress, γ—shear rate, β_0—parameters of the initial state, ξ—thixotropic parameters, τ_0—yield stress, μ—plastic viscosity, n—flow index, t—shearing time
Flatt and Bowen [101]	$\tau_0 \cong \frac{A_0 a^*}{d^2H^2} f_\sigma^* \frac{\phi^2\left(\phi-\phi_{perc}\right)}{\phi_m(\phi_m-\phi)}$	τ_0—yield stress, d—average particle size, f_σ^*—a function of the particle size distribution, m—pre-factor depending on the particle size distribution, a^*—radius of curvature of the contact point, H—separation distance from the surface to the surface, A_0—non-retarded Hamaker constant, ϕ_{perc}—percolation threshold, ϕ_m—maximum packing fraction, ϕ—packing fraction

6. Conclusions and outlook

The CPB technology is an effective method to solve the accumulation of tailings and underground goaves. Due to the high shearing, high concentration, and multiscale characteristics of the granular system in the mixing process, the evolution of mechanics and mesostructure is complicated, and it becomes quite challenging to control the paste quality. Paste rheology is the theoretical basis of CPB technology. This paper summarizes the progress in the research of the rheological properties in the mixing process under the mesomachical and mesostructural views.

The research on the rheological properties of the paste in the mixing process has the following limitations.

(1) In terms of the multiscale interparticle mechanics under shearing, there is a lack of understanding of the mechanisms involved. Currently, it is impossible to quantify the influence of mechanics on the macroscopic properties of the paste.

(2) The qualitative analysis limited the research on the structural evolution of multiscale granular systems under shearing. The paste mixing research has advanced to determine macroscopic parameters and qualitatively describe mesostructure evolution. However, it has been challenging to characterize the behavior of the structural evolution in multiscale granular systems up until now.

(3) It is necessary to develop a mesoscopic rheological model of the paste under shearing. The mesomechanics and structural evolution affect the macro-rheological properties of the paste. Macro-rheological models have limitations in characterizing the rheological properties of paste in the mixing process.

Optimizing the mixing process of the CPB technology is necessary to improve its application performance. Further research on mixing processes can be conducted using the following perspectives to prepare a homogeneous paste. It is essential to analyze the mixing process of the paste from the perspectives of mesomechanics and structural evolution. As a result, mesoscopic rheological models can be constructed for paste with strong shearing effects. In addition, extensive laboratory and industrial experiments are necessary to obtain the paste's rheological properties under different conditions. A machine learning prediction model can be developed by taking shearing conditions as input variables and rheological parameters as output variables. The model can be used to predict the rheological properties of the paste under shearing conditions. Moreover, fluidity is not the only indicator for evaluating CPB. Low yield stress and plastic viscosity can improve the paste fluidity; however, it will also increase the risk of paste slurry segregation, making it difficult to guarantee the strength of the filling body. To ensure that the paste meets the engineering requirements, it is important to consider the fluidity of the paste and the strength of the filling body when designing the mixing process. Finally, based on the rheological properties of the paste and the strength of the filling body, the shearing effect provided by various blades and mixers in the mixing process can be quantitatively characterized. In this way, the mixer can be optimized and designed.

Overall, the mesomechanics and structural evolution during the mixing process must be studied in the future to obtain the mixing rheological law of all solid waste paste with homogenous characteristics.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Z.E. Ruan, A.X. Wu, H.Z. Jiao, *et al*., Advances and trends on thickening of full-tailings slurry in China, *Chin. J. Nonferrous Met.*, 32(2022), p. 286.

[2] T. Gao, W. Sun, Z. Liu, and H. Cheng, Investigation on fracture characteristics and failure pattern of inclined layered cemented tailings backfill, *Constr. Build. Mater.*, 343(2022), art. No. 128110.

[3] J.X. Li, W. Sun, Q.Q. Li, S. Chen, M.L. Yuan, and H. Xia, Influence of layered angle on dynamic characteristics of backfill under impact loading, *Minerals*, 12(2022), No. 5, art. No. 511.

[4] W. Sun, S.Y. Zhang, J.X. Li, and Z.Y. Li, Experimental study on energy dissipation of layered backfill under impact load, *Constr. Build. Mater.*, 347(2022), art. No. 128478.

[5] L. Liu, J. Xin, C. Huan, *et al*., Effect of curing time on the mesoscopic parameters of cemented paste backfill simulated using the particle flow code technique, *Int. J. Miner. Metall. Mater.*, 28(2021), No. 4, p. 590.

[6] A.X. Wu, Z.E. Ruan, and J.D. Wang, Rheological behavior of paste in metal mines, *Int. J. Miner. Metall. Mater.*, 29(2022), No. 4, p. 717.

[7] C. Qi and A. Fourie, Cemented paste backfill for mineral tailings management: Review and future perspectives, *Miner. Eng.*, 144(2019), art. No. 106025.

[8] S. Wang, X. Song, M. Wei, *et al*., Flow characteristics of fresh cemented paste backfill containing flocculant under variable shear rate based on water migration, *Min. Metall. Explor.*, 39(2022), No. 3, p. 1189.

[9] H. Jiang, M. Fall, E. Yilmaz, Y. Li, and L. Yang, Effect of mineral admixtures on flow properties of fresh cemented paste backfill: Assessment of time dependency and thixotropy, *Powder Technol.*, 372(2020), p. 258.

[10] J. Qiu, Z. Guo, L. Yang, H. Jiang, and Y. Zhao, Effects of packing density and water film thickness on the fluidity behaviour of cemented paste backfill, *Powder Technol.*, 359(2020), p. 27.

[11] S.G. Liu and M. Fall, Fresh and hardened properties of cemented paste backfill: Links to mixing time, *Constr. Build. Mater.*, 324(2022), art. No. 126688.

[12] R. Collet, D. Oulahna, A. De Ryck, P.H. Jezequel, and M. Martin, Mixing of a wet granular medium: Effect of the particle size, the liquid and the granular compacity on the intensity consumption, *Chem. Eng. J.*, 164(2010), No. 2-3, p. 299.

[13] J.H. Kim, H.J. Yim, and R.D. Ferron, *In situ* measurement of the rheological properties and agglomeration on cementitious pastes, *J. Rheol.*, 60(2016), No. 4, p. 695.

[14] X. Li, C.P. Li, Z.E. Ruan, B.H. Yan, H.Z. Hou, and L. Chen, Analysis of particle migration and agglomeration in paste mixing based on discrete element method, *Constr. Build. Mater.*, 352(2022), art. No. 129007.

[15] C.P. Li, Z.H. Huang, Z.E. Ruan, and S.Y. Wang, Analysis of the research progress in the mechanism of particle mechanics action on the rheological behavior of paste in metal mines, *Chin. J. Eng.*, 44(2022), No. 8, p. 1293.

[16] F. Chen, R. Su, L. Yang, *et al*., Effect of mixing speed on rheological properties of cemented paste backfill, *Chin. J. Nonferrous Met.*, 32(2022), No. 11, p. 3541.

[17] X. Li, C.P. Li, B.H. Yan, and H.Z. Hou, Analysis of the influence factors of paste stirring based on discrete element method, *Met. Mine*, 2021, No. 3, p. 19.

[18] L.H. Yang, *Research on the Rheological Characteristics and the Mechanism of Shear Action during Paste Mixing* [Dissertation], University of Science and Technology Beijing, Beijing, 2020.

[19] B.J. Ennis, J. Li, and P. Robert, The influence of viscosity on the strength of an axially strained pendular liquid bridge, *Chem. Eng. Sci.*, 45(1990), No. 10, p. 3071.

[20] S.M. Iveson, P.A.L. Wauters, S. Forrest, J.D. Litster, G.M.H. Meesters, and B. Scarlett, Growth regime map for liquid-bound granules: Further development and experimental validation, *Powder Technol.*, 117(2001), No. 1-2, p. 83.

[21] M. Benali, V. Gerbaud, and M. Hemati, Effect of operating conditions and physico–chemical properties on the wet granulation kinetics in high shear mixer, *Powder Technol.*, 190(2009), No. 1-2, p. 160.

[22] H. Kristensen, P. Holm, and T. Schaefer, Mechanical properties of moist agglomerates in relation to granulation mechanisms part I. Deformability of moist, densified agglomerates, *Powder Technol.*, 44(1985), No. 3, p. 227.

[23] H. Takenaka, Y. Kawashima, and J.U.N. Hishida, The effects of interfacial physical properties on the cohesive forces of moist powder in air and in liquid, *Chem. Pharm. Bull.*, 29(1981), No. 9, p. 2653.

[24] N. Roussel, A. Lemaître, R.J. Flatt, and P. Coussot, Steady state flow of cement suspensions: A micromechanical state of the art, *Cem. Concr. Res.*, 40(2010), No. 1, p. 77.

[25] N.J. Wagner and J.F. Brady, Shear thickening in colloidal dispersions, *Phys. Today*, 62(2009), No. 10, p. 27.

[26] R.J. Flatt, Dispersion forces in cement suspensions, *Cem. Concr. Res.*, 34(2004), No. 3, p. 399.

[27] W. Wu, R.F. Giese, and C.J. van Oss, Stability versus flocculation of particle suspensions in water—Correlation with the

extended DLVO approach for aqueous systems, compared with classical DLVO theory, *Colloids Surf. B*, 14(1999), No. 1-4, p. 47.
[28] J.R. Royer, D.L. Blair, and S.D. Hudson, Rheological signature of frictional interactions in shear thickening suspensions, *Phys. Rev. Lett.*, 116(2016), No. 18, art. No. 188301.
[29] C. Clavaud, A. Bérut, B. Metzger, and Y. Forterre, Revealing the frictional transition in shear-thickening suspensions, *Proc. Natl. Acad. Sci. USA*, 114(2017), No. 20, p. 5147.
[30] G.V. Franks, Z.W. Zhou, N.J. Duin, and D.V. Boger, Effect of interparticle forces on shear thickening of oxide suspensions, *J. Rheol.*, 44(2000), No. 4, p. 759.
[31] J. Mewis and N.J. Wagner, *Colloidal Suspension Rheology*, Cambridge University Press, Cambridge, 2012.
[32] S. Gallier, E. Lemaire, F. Peters, and L. Lobry, Rheology of sheared suspensions of rough frictional particles, *J. Fluid Mech.*, 757(2014), p. 514.
[33] R.V. More and A.M. Ardekani, Roughness induced shear thickening in frictional non-Brownian suspensions: A numerical study, *J. Rheol.*, 64(2020), No. 2, p. 283.
[34] É. Guazzelli and O. Pouliquen, Rheology of dense granular suspensions, *J. Fluid Mech.*, 852(2018), art. No. P1.
[35] R. Mari, R. Seto, J.F. Morris, and M.M. Denn, Shear thickening, frictionless and frictional rheologies in non-Brownian suspensions, *J. Rheol.*, 58(2014), No. 6, p. 1693.
[36] J. Yammine, M. Chaouche, M. Guerinet, M. Moranville, and N. Roussel, From ordinary rhelogy concrete to self compacting concrete: A transition between frictional and hydrodynamic interactions, *Cem. Concr. Res.*, 38(2008), No. 7, p. 890.
[37] L.F. Nielsen, Rheology of some fluid extreme composites: Such as fresh self-compacting concrete, *Nord. Concr. Res.*, 27(2001), p. 83.
[38] P. Coussot and C. Ancey, Rheophysical classification of concentrated suspensions and granular pastes, *Phys. Rev. E*, 59(1999), No. 4, p. 4445.
[39] A.B. Yu, C.L. Feng, R.P. Zou, and R.Y. Yang, On the relationship between porosity and interparticle forces, *Powder Technol.*, 130(2003), No. 1-3, p. 70.
[40] A. Burggraeve, T. Monteyne, C. Vervaet, J.P. Remon, and T. De Beer, Process analytical tools for monitoring, understanding, and control of pharmaceutical fluidized bed granulation: A review, *Eur. J. Pharm. Biopharm.*, 83(2013), No. 1, p. 2.
[41] S.M. Iveson, J.D. Litster, K. Hapgood, and B.J. Ennis, Nucleation, growth and breakage phenomena in agitated wet granulation processes: A review, *Powder Technol.*, 117(2001), No. 1-2, p. 3.
[42] P. Suresh, I. Sreedhar, R. Vaidhiswaran, and A. Venugopal, A comprehensive review on process and engineering aspects of pharmaceutical wet granulation, *Chem. Eng. J.*, 328(2017), p. 785.
[43] H. Leuenberger, M. Puchkov, E. Krausbauer, and G. Betz, Manufacturing pharmaceutical granules: Is the granulation end-point a myth? *Powder Technol.*, 189(2009), No. 2, p. 141.
[44] D. Lievano, S. Velankar, and J.J. McCarthy, The rupture force of liquid bridges in two and three particle systems, *Powder Technol.*, 313(2017), p. 18.
[45] C.L. Flemmer, On the regime boundaries of moisture in granular materials, *Powder Technol.*, 66(1991), No. 2, p. 191.
[46] T.T. Vo, P. Mutabaruka, S. Nezamabadi, *et al.*, Mechanical strength of wet particle agglomerates, *Mech. Res. Commun.*, 92(2018), p. 1.
[47] P. Jarvis, B. Jefferson, J. Gregory, and S.A. Parsons, A review of floc strength and breakage, *Water Res.*, 39(2005), No. 14, p. 3121.
[48] G.K. Reynolds, J.S. Fu, Y.S. Cheong, M.J. Hounslow, and A.D. Salman, Breakage in granulation: A review, *Chem. Eng. Sci.*, 60(2005), No. 14, p. 3969.
[49] J.S. Ramaker, M.A. Jelgersma, P. Vonk, and N.W.F. Kossen, Scale-down of a high-shear pelletisation process: Flow profile and growth kinetics, *Int. J. Pharm.*, 166(1998), No. 1, p. 89.
[50] R.D. Ferron, S. Shah, E. Fuente, and C. Negro, Aggregation and breakage kinetics of fresh cement paste, *Cem. Concr. Res.*, 50(2013), p. 1.
[51] J.E. Wallevik, Rheological properties of cement paste: Thixotropic behavior and structural breakdown, *Cem. Concr. Res.*, 39(2009), No. 1, p. 14.
[52] P.N. Hiremath and S.C. Yaragal, Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete, *Constr. Build. Mater.*, 141(2017), p. 271.
[53] B. Cazacliu and N. Roquet, Concrete mixing kinetics by means of power measurement, *Cem. Concr. Res.*, 39(2009), No. 3, p. 182.
[54] D. Jiao, C. Shi, and Q. Yuan, Influences of shear-mixing rate and fly ash on rheological behavior of cement pastes under continuous mixing, *Constr. Build. Mater.*, 188(2018), p. 170.
[55] D. Han and R.D. Ferron, Influence of high mixing intensity on rheology, hydration, and microstructure of fresh state cement paste, *Cem. Concr. Res.*, 84(2016), p. 95.
[56] E. Brown and H.M. Jaeger, Through thick and thin, *Science*, 333(2011), No. 6047, p. 1230.
[57] H.J. Wang, L.H. Yang, H. Li, X. Zhou, and X.T. Wang, Using coupled rheometer-FBRM to study rheological properties and microstructure of cemented paste backfill, *Adv. Mater. Sci. Eng.*, 2019(2019), art. No. 6813929.
[58] L.H. Yang, H.J. Wang, H. Li, and X. Zhou, Effect of high mixing intensity on rheological properties of cemented paste backfill, *Minerals*, 9(2019), No. 4, art. No. 240.
[59] M. Yang and H.M. Jennings, Influences of mixing methods on the microstructure and rheological behavior of cement paste, *Adv. Cem. Based Mater.*, 2(1995), No. 2, p. 70.
[60] L.H. Yang, H.J. Wang, A.X. Wu, *et al.*, Effect of mixing time on hydration kinetics and mechanical property of cemented paste backfill, *Constr. Build. Mater.*, 247(2020), art. No. 118516.
[61] C.D. Min, X.B. Li, S.Y. He, *et al.*, Effect of mixing time on the properties of phosphogypsum-based cemented backfill, *Constr. Build. Mater.*, 210(2019), p. 564.
[62] F.D. Larrard, *Concrete Mixture Proportioning: A Scientific Approach*, CRC Press, London, 1999.
[63] T. Lecompte, A. Perrot, V. Picandet, H. Bellegou, and S. Amziane, Cement-based mixes: Shearing properties and pore pressure, *Cem. Concr. Res.*, 42(2012), No. 1, p. 139.
[64] S. Cao, E. Yilmaz, and W.D. Song, Evaluation of viscosity, strength and microstructural properties of cemented tailings backfill, *Minerals*, 8(2018), No. 8, art. No. 352.
[65] S.Y. Wang, A.X. Wu, Z.E. Ruan, and S.M. Chen, Rheological properties of paste slurry and influence factors based on pipe loop test, *J. Cent. South Univ. Sci. Technol.*, 49(2018), No. 10, p. 2519.
[66] Z.E. Ruan, A.X. Wu, R. Bürger, *et al.*, Effect of interparticle interactions on the yield stress of thickened flocculated copper mineral tailings slurry, *Powder Technol.*, 392(2021), p. 278.
[67] B.L. Xiao, M. Fall, and A. Roshani, Towards understanding the rheological properties of slag-cemented paste backfill, *Int. J. Min. Reclam. Environ.*, 35(2021), No. 4, p. 268.
[68] G. Jiang, A. Wu, Y. Wang, and J. Li, The rheological behavior of paste prepared from hemihydrate phosphogypsum and tailing, *Constr. Build. Mater.*, 229(2019), art. No. 116870.
[69] General Administration of Quality Supervision, People's Republic of China, GB/T39489–2020: *Technical Specification for the Total Tailings Paste Backfill*, Standards Press of China, Beijing, 2020.

[70] D.W. Jiao, C.J. Shi, Q. Yuan, X.P. An, Y. Liu, and H. Li, Effect of constituents on rheological properties of fresh concrete—A review, *Cem. Concr. Compos.*, 83(2017), p. 146.
[71] L.H. Yang, H.J. Wang, A.X. Wu, P. Xing, and H.W. Gao, Thixotropy of unclassified pastes in the process of stirring and shearing, *Chin. J. Eng.*, 38(2016), No. 10, p. 1343.
[72] W.B. Xu, B.G. Yang, S.L. Yang, and P. Dang, Experimental study on correlativity between rheological parameters and grain grading of coal gauge backfill slurry, *J. Cent. South Univ. Sci. Technol.*, 47(2016), No. 4, p. 1282.
[73] A.X. Wu and H.J. Wang, *Theory and Technology of Paste Backfill in Metal Mines*, Science Press, Beijing, 2015.
[74] F. Sofra, Rheological properties of fresh cemented paste tailings, [in] *Paste Tailings Management*, Springer International Publishing, Switzerland, 2017, p. 33.
[75] X.H. Liu, A.X. Wu, H.J. Wang, and Y.M. Wang, Influence mechanism and calculation model of CPB rheological parameters, *Chin. J. Eng.*, 39(2017), No. 2, p. 190.
[76] N. Roussel, Steady and transient flow behaviour of fresh cement pastes, *Cem. Concr. Res.*, 35(2005), No. 9, p. 1656.
[77] V. Wong, K.W. Chan, and A.K.H. Kwan, Applying theories of particle packing and rheology to concrete for sustainable development, *Organiz. Technol. Manage. Constr. Int. J.*, 5(2013), No. 2, p. 844.
[78] A.K.H. Kwan, K.W. Chan, and V. Wong, A 3-parameter particle packing model incorporating the wedging effect, *Powder Technol.*, 237(2013), p. 172.
[79] D.M. Liu, Particle packing and rheological property of highly-concentrated ceramic suspensions: φ_m determination and viscosity prediction, *J. Mater. Sci.*, 35(2000), No. 21, p. 5503.
[80] R.D. Hooton, M.R. Geiker, M. Brandl, L.N. Thrane, and L.F. Nielsen, On the effect of coarse aggregate fraction and shape on the rheological properties of self-compacting concrete, *Cement Concrete Aggr.*, 24(2002), No. 1, art. No. 3.
[81] H.C. Long, J.X. Xia, and B. Cao, Effect of coarse/fine materials ratio on rheological properties, *Min. Metall. Eng.*, 37(2017), No. 2, p. 6.
[82] H.J. Wang, G.C. Li, A.X. Wu, *et al*., Study on rheological properties of paste with different corase aggregate, *Min. Res. Dev.*, 34(2014), No. 7, p. 59.
[83] Y. Liu, J.P. Li, Y. Lu, and Y.M. Zhou, Experimental studying of coal gangue large particle size coarse aggregate ratio to filling paste property, *Coal Min. Technol.*, 21(2016), No. 5, p. 1.
[84] J. Hu and K. Wang, Effect of coarse aggregate characteristics on concrete rheology, *Constr. Build. Mater.*, 25(2011), No. 3, p. 1196.
[85] J. Wu, M. Feng, X. Mao, *et al*., Particle size distribution of aggregate effects on mechanical and structural properties of cemented rockfill: Experiments and modeling, *Constr. Build. Mater.*, 193(2018), p. 295.
[86] J. Wu, H. Jing, Y. Gao, Q. Meng, Q. Yin, and Y. Du, Effects of carbon nanotube dosage and aggregate size distribution on mechanical property and microstructure of cemented rockfill, *Cem. Concr. Compos.*, 127(2022), art. No. 104408.
[87] A.X. Wu, H. Li, H.Y. Cheng, Y.M. Wang, C.P. Li, and Z.E. Ruan, Status and prospects of researches on rheology of paste backfill using unclassified tailings (Part 1): Concepts, characteristics and models, *Chin. J. Eng.*, 42(2020), No. 7, p. 803.
[88] H.A. Barnes, Thixotropy—A review, *J. Non-Newton. Fluid Mech.*, 70(1997), No. 1-2, p. 1.
[89] K. Vance, G. Sant, and N. Neithalath, The rheology of cementitious suspensions: A closer look at experimental parameters and property determination using common rheological models, *Cem. Concr. Compos.*, 59(2015), p. 38.
[90] Y. Qian and S. Kawashima, Distinguishing dynamic and static yield stress of fresh cement mortars through thixotropy, *Cem. Concr. Compos.*, 86(2018), p. 288.
[91] X. Chateau, G. Ovarlez, and K.L. Trung, Homogenization approach to the behavior of suspensions of noncolloidal particles in yield stress fluids, *J. Rheol.*, 52(2008), No. 2, p. 489.
[92] C.P. Li, B.H. Yan, and H.Z. Hou, Rheological behavior of solid–liquid conversion stage of unclassified tailings backfill paste, *Chin. J. Nonferrous Met.*, 30(2020), No. 5, p. 1209.
[93] H.Y. Cheng, S.C. Wu, X.Q. Zhang, and A.X. Wu, Effect of particle gradation characteristics on yield stress of cemented paste backfill, *Int. J. Miner. Metall. Mater.*, 27(2020), No. 1, p. 10.
[94] A. Wu, Y. Wang, and H. Wang, Estimation model for yield stress of fresh uncemented thickened tailings: Coupled effects of true solid density, bulk density, and solid concentration, *Int. J. Miner. Process.*, 143(2015), p. 117.
[95] T.D. Nguyen, T.H. Tran, and N.D. Hoang, Prediction of interface yield stress and plastic viscosity of fresh concrete using a hybrid machine learning approach, *Adv. Eng. Inform.*, 44(2020), art. No. 101057.
[96] Y.H. Niu, H.Y. Cheng, S.C. Wu, J.L. Sun, and J.X. Wang, Rheological properties of cemented paste backfill and the construction of a prediction model, *Case Stud. Constr. Mater.*, 16(2022), art. No. e01140.
[97] W.E. Worrall and S. Tuliani, Viscosity changes during the ageing of clay-water suspensions, *Trans. Brit. Ceram. Soc.*, 63(1964), p. 167.
[98] E.A. Toorman, Modelling the thixotropic behaviour of dense cohesive sediment suspensions, *Rheol. Acta*, 36(1997), No. 1, p. 56.
[99] N. Roussel, A thixotropy model for fresh fluid concretes: Theory, validation and applications, *Cem. Concr. Res.*, 36(2006), No. 10, p. 1797.
[100] L.F. Zhang, H.J. Wang, A.X. Wu, B. Klein, and X.J. Zhang, A constitutive model for thixotropic cemented tailings backfill pastes, *J. Non-Newton. Fluid Mech.*, 295(2021), art. No. 104548.
[101] R.J. Flatt and P. Bowen, Yodel: A yield stress model for suspensions, *J. Am. Ceram. Soc.*, 89(2006), No. 4, p. 1244.
[102] Z.B. Peng, E. Doroodchi, B. Moghtaderi, and G.M. Evans, A DEM-based analysis of the influence of aggregate structure on suspension shear yield stress, *Adv. Powder Technol.*, 23(2012), No. 4, p. 437.
[103] P. Coussot, Q.D. Nguyen, H.T. Huynh, and D. Bonn, Viscosity bifurcation in thixotropic, yielding fluids, *J. Rheol.*, 46(2002), No. 3, p. 573.
[104] P.C.F. Møller, J. Mewis, and D. Bonn, Yield stress and thixotropy: On the difficulty of measuring yield stresses in practice, *Soft Matter*, 2(2006), No. 4, p. 274.