Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 24(2014) 2954−2963
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Coupled effect of cement hydration and temperature on rheological properties of fresh cemented tailings backfill slurry

Di WU[1,2], Si-jing CAI[3], Gang HUANG[3]

1. Faculty of Resources and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China;
2. State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing 100083, China;
3. School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China

Received 30 August 2013; accepted 26 December 2013

Abstract: The fluidity of fresh cemented tailings backfill (CTB) slurry depends on its rheological properties. Hence, it is crucial to understand the rheology of fresh CTB slurry, which is related to the cement hydration progress and temperature evolution within CTB mixtures. For this reason, a numerical model was developed to predict the evolution of the rheological properties of fresh CTB slurry under the coupled effect of cement hydration and temperature. Experiments were conducted to investigate the rheological behaviours of the fresh CTB slurry. By comparing the simulated results with the experimental ones, the availability of this developed model was validated. Thereafter, the model was used to demonstrate the coupled effect of cement hydration and temperature on the evolution of fresh CTB slurry's rheological properties, under various conditions (initial CTB temperature, cement to tailings ratio, and water to cement ratio). The obtained results are helpful to better understanding the rheology of CTB slurry.

Key words: cemented tailings backfill (CTB); hydration; temperature; rheology; coupled model

1 Introduction

Cemented tailings backfill (CTB) slurry is one kind of non-Newtonian fluid, which is prepared by mixing cement, tailings and water [1]. The utilization of CTB technology allows waste tailings to be placed underground, which not only reduces the surface discharge of solid waste, but also provides underground supports [2]. Because of these advantages of CTB technology, it is being widely and intensively employed in global mining industry [3].

Generally, the freshly made CTB slurry is transported into underground stopes through pipeline. Therefore, the fresh CTB slurry should be flowable and transportable enough to ensure the delivery smoothly and efficiently. Otherwise, some problems (e.g., pipeline clogging) may occur, which would cause serious consequences, such as delaying mining production and increasing cost. However, the fluidity and transportability of fresh CTB slurry are dependent on its rheological properties [4], which are not only influenced by its own characteristics (e.g., solid concentration and mix proportion of the CTB mixtures), but also affected by some external factors, such as temperature and cement hydration process.

Of these factors, the internal properties of the fresh CTB slurry can be easily modified and adjusted (e.g., changing the solid percentage of the slurry) to improve its fluidity and thus to meet the transportation requirement. Nevertheless, the external factors are difficult or even impossible to adjust. For instance, friction between the fresh CTB slurry and inner walls of the pipe is inevitable. This causes thermal loading on the flowing slurry, thus increasing its temperature. This temperature rise will significantly affect the slurry's rheological properties [5].

Mining depth is another significant factor. Due to the geothermic gradient, the underground environmental temperature increases in direct proportion to the mining

Foundation item: Project (SKLCRSM13KFB05) supported by State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing)
Corresponding author: Di WU; Tel: +86-18710162586; E-mail: tauo123@163.com
DOI: 10.1016/S1003-6326(14)63431-2

depth. This temperature rise will in turn affect the underground CTB temperatures, thus exerting an influence on the evolution of CTB slurry's rheological behaviour. For these reasons, it is essential to study the effect of various temperature loading conditions on the rheology of CTB slurry.

As one of the most significant heat sources, cement hydration process releases considerable amount of heat, contributing to the temperature development [6] within CTB mixtures, which in turn affects the CTB slurry's rheological properties. This temperature rise caused by cement hydration then affects the hydration process since a higher temperature is favourable for accelerating the cement hydration process [7].

Therefore, it can be determined that within fresh CTB mixtures, the cement hydration and temperature development interact with each other and together affect the rheological behaviours of CTB slurry. For this reason, it is vitally important to study the coupled effect of cement hydration and temperature rise on the rheology of fresh CTB slurry.

However, after being placed into underground stopes and naturally cured for a certain period, the fresh CTB mixtures should form hardened CTB structures to support roofs that provide a safe working environment for miners, as well as support pillars for improving recovery. Therefore, the adjustment of CTB slurries' internal features should fulfill the strength requirement of hardened CTB structures. Accordingly, the uniaxial compressive strength (UCS) is introduced to evaluate the mechanical stability of CTB structures [6]. Thus, to develop a favourable design for preparing CTB mixtures, both the rheological properties of fresh CTB slurries and the mechanical characteristics of hardened CTB structures should be considered at the same time. Although this paper is focused on the rheology of fresh CTB slurry, the UCS of hardened CTB structures is taken into consideration as well.

This paper is organized as follows: first, a mathematical model was numerically developed by coupling the equations of cement hydration, heat transfer and rheology; secondly, an experimental rheometer test was conducted on the freshly prepared CTB slurry; thirdly, the developed model was validated against the previous experimental results and put into application, and the coupled effects of cement hydration and temperature variation on the rheological properties of fresh CTB slurry under different boundary conditions were discussed and demonstrated; finally, the conclusions were presented.

2 Development of mathematical model

As demonstrated above, the rheological behaviour of fresh CTB slurry is affected by cement hydration and accompanied thermal process. Besides, the progress of cement hydration and the thermal process also interact with each other: the progress of cement hydration releases significant amount of heat to contribute to temperature development and at the same time high temperature can accelerate the hydration progress. The engineering simulation software COMSOL Multiphysics [8] is widely applied to conducting coupled modeling. Consequently, in the present study, the built-in "Heat Transfer Module", "CFD Module" and "Chemical Reaction Engineering Module" within COMSOL Multiphysics can be coupled together to analyze the coupled effect of cement hydration and the temperature variation on the rheological behaviour of fresh CTB slurry. The basic mathematical equation is applied to the modeling as follows:

$$\rho_c C_c \frac{\partial T_c}{\partial t} + \rho_c C_c u_c \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{1}$$

where ρ_c, C_c and k are the density, specific heat capacity and thermal conductivity of the fresh CTB slurry, respectively; u_c is the velocity field (i.e., the volumetric flow rate) of the fresh CTB slurry; Q is the heat source term.

2.1 Hydration equations

Cement hydration starts when the cement is mixed with water. The extent of this hydration progress can be described by the degree of cement hydration [9], which is introduced to represent the proportion of reacted cement, and its definition [10] can be expressed by the following equation:

$$\alpha(t) = \frac{H(t)}{H_T} \tag{2}$$

where $\alpha(t)$ is the degree of cement hydration at the time t; $H(t)$ is the accumulated heat released by cement hydration until time t; H_T is the total heat when all the cement reacts ultimately.

In order to reveal the effect of time t on the degree of cement hydration, SCHINDLER and FOLLIARD [11] obtained the following expression:

$$\alpha(t) = \alpha_f \cdot \exp\left[-\left(\frac{\tau_T}{t}\right)^{\beta}\right] \tag{3}$$

where t_T is the time parameter of cement hydration when the temperature of fresh CPB is T; β is the shape parameter of cement hydration; α_f is the ultimate degree of cement hydration, which can be calculated in the following form [12]:

$$\alpha_f = \frac{1.031\, w/c}{0.194 + w/c} \tag{4}$$

where w/c is water-to-cement ratio.

According to the definition, the degree of cement hydration is the ratio of reacted cement to the total cement. Hence, the final degree of cement hydration cannot exceed 1% unless all the compounds of cement hydrate completely. Only in this condition, the percentage of the reacted cement could be 100%, and the value of α_f can be 1. For Eq. (4), when the value of w/c is 6.258, α_f=1. Therefore, if the value of w/c is greater than 6.258, α_f will also be greater than 1, which is impossible. This is because the above equation is obtained by studying on concrete, for which the value of w/c is only 0.2−0.6; thus the value of α_f can never be beyond 1 and the above equation is valid. Therefore, before applying this equation to CTB mixtures, some assumptions need to be made:

$$\alpha_f = \begin{cases} \dfrac{1.031\,w/c}{0.194 + w/c},\ w/c < 6.258 \\ 1,\ w/c \geq 6.258 \end{cases} \tag{5}$$

2.2 Heat equations

Since cement hydration process releases significant amount of heat that can bring about the temperature development in fresh CTB slurry, which would furthermore influence its rheological properties and thus its flowing behaviors, it is essential to analyze this thermal process and determine the associated temperature evolution of the fresh CTB slurry. As a result, the expression obtained by SCHINDLER and FOLLIARD [11] is employed to illustrate this thermal progress, during which cement hydration, heat, temperature and elapsed time are linked together:

$$Q_{ch} = H_{CEM} \cdot \left(\frac{\tau_{T_c}}{t}\right)^{\beta} \cdot \left(\frac{\beta \cdot \tau_{T_c}}{\tau_{T_r} \cdot t}\right) \cdot \alpha(t)\frac{E}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T_c}\right) \tag{6}$$

where Q_{ch} is the heat generating rate of cement hydration; H_{CEM} is the heat generated by cement hydration; T_c is the temperature of the fresh CTB slurry; T_r is the reference temperature; τ_{T_c} and τ_{T_r} are the time parameters of cement hydration at temperature T_c and T_r respectively; β is the shape parameter of cement hydration; $\alpha(t)$ is the degree of cement hydration at elapsed time t; E is the apparent activation energy; R is the mole gas constant.

Furthermore, the following equation [10] was proposed to reveal the effect of the heat produced by cement hydration on the temperature evolution of fresh CTB slurry versus time:

$$\rho_c C_c \frac{dT_c}{dt} = Q_{ch} \tag{7}$$

where ρ_c and C_c are the density and specific heat capacity of the fresh CTB slurry, respectively.

In Eq. (6), the term E varies with the change of the CTB slurry's temperature [13], which is constant with the value of 33500 J/mol when T_c is equal to or higher than 20 °C and on the contrary, when T_c is lower than 20 °C, there is

$$E(T_c) = 33500 + 1470(20 - T_c) \tag{8}$$

Actually, cement hydration includes all the chemical reactions of the compounds that comprise cement. Therefore, the term H_{CEM} in Eq. (6) is the total heat [10] that is produced by all the compounds:

$$H_{CEM} = 500p_{C_3S} + 260p_{C_2S} + 866p_{C_3A} + 420p_{C_4AF} + 624p_{SO_3} + 1186p_{FreeCaO} + 850p_{MgO} \tag{9}$$

where p_i is the mass ratio of the i-th compound in terms of total cement content.

In addition to the heat from cement hydration, the heat transfer process between the fresh CTB slurry and its surrounding atmosphere can also contribute to the temperature evolution within fresh CTB slurry. For this reason, Fourier'S law is presented here to demonstrate this heat transfer process induced by temperature gradient between the fresh CTB slurry and its surroundings [7]:

$$Q = -k \cdot \nabla T \tag{10}$$

where Q is the transferred heat flux; k is the thermal conductivity of the fresh CTB slurry; ∇T is the temperature gradient. Within the current study, the thermal conductivity of the fresh CTB slurry, which is not affected by the evolution of cement hydration and temperature, is considered to be constant, with the evidence experimentally proved by CELESTIN and FALL [14].

2.3 Rheology equations

According to the conservation of momentum, the following expression [15] can be applied to fresh CTB slurry:

$$\rho_c \frac{du}{dt} = \rho_c u_c = \nabla\sigma + \rho_c g \tag{11}$$

where ρ_c and u_c are the density and volumetric flowing rate of the fresh CTB slurry, respectively; σ is the stress; g is the gravitational acceleration.

The fresh CTB flow performs non-Newtonian behaviors, and its fluid rheology can be described by Bingham model [16], which is a basic non-linear rheological model and can be represented by the following equation:

$$\tau_s = \tau_y + \mu_B\dot{\gamma} \tag{12}$$

where τ_s, τ_y and μ_B are the shear stress, yield stress and Bingham plastic viscosity of the fresh CTB flow; $\dot{\gamma}$ is the shearing rate.

It is well-known that fluid viscosity is temperature dependent, and the influence of temperature on the viscosity of fresh CTB slurry can be expressed by the following equation [15]:

$$\mu_c = \mu_r \cdot \exp[E/(RT_c)] \tag{13}$$

where μ_c and μ_r are the viscosities of fresh CTB slurry at T_c and T_r respectively, and the meanings of T_c and T_r have been given in Eq. (6).

PAPO and CAUFIN [17] achieved the following equation to reveal the effect of cement hydration process on the viscosity of cement-based materials such as cement pates and fresh CTB slurry:

$$\mu_c = \mu_{c0} + (1000 - \mu_{c0}) \cdot (t/t_v)^n \tag{14}$$

where μ_{c0} is the initial viscosity of the fresh CTB slurry; n is a parameter indicating the kinetics of cement hydration progress; t_v is the moment at which the slurry reaches a relatively high characteristic viscosity, which can be further calculated by the equation of water-to-cement ratio as follows [17]:

$$t_v = t_{v0} + X\left[w/c - (w/c)_0\right]^Y \tag{15}$$

where t_{v0} is the initial value of t_v; $(w/c)_0$ is the initial value of w/c; X and Y are the experimentally determined parameters, which are listed in Table 1.

Table 1 Parameters in Equation (15) [17]

Cement type	t_{v0}	X	Y
325#	144	1850	1.27
425#	111	5580	1.54
525#	93	22300	2.11

By integrating equations (13) and (14), the coupled effect of temperature and cement hydration on the viscosity of fresh CTB slurry can be obtained:

$$\mu_c = \mu_r \cdot \exp[E/(RT_{c0})] + [1000 - \mu_r \cdot \exp(E/(RT_{c0}))] \cdot (t/t_v)^n \tag{16}$$

where T_{c0} is the initial temperature of the fresh CTB slurry.

Additionally, PETIT et al [18] proposed the following Eq. (17) to reveal the coupled effect of cement hydration and temperature variation on the yield stress of mortar. Since mortar and CTB slurry are both cement-based materials, their rheological properties are just related to the cemented products, without regarding to other factors such as the aggregates of mortar or tailings in CTB slurry. Therefore, the expression demonstrating the method of calculating the yield stress of fresh mortar at moment t is also applicable to fresh CTB slurry as follows:

$$\tau_y(t) = \tau_{y0}(T) + \theta \cdot \exp(\varepsilon/T) \cdot t \tag{17}$$

where $\tau_{y0}(T)$ is the initial yield stress of fresh CTB slurry at a given temperature T; θ and ε are experimental constants depending on the mixing proportion of fresh CTB slurry.

2.4 Model coupling

Through combing the previous three sets of equations, the coupled model can be achieved and expressed mathematically in the following form:

$$\begin{aligned} & H_{\mathrm{CEM}} \cdot \left(\frac{\tau_{T_c}}{t}\right)^{\beta} \cdot \left(\frac{\beta \cdot \tau_{T_c}}{\tau_{T_r} \cdot t}\right) \cdot \left(\frac{1.031 \cdot w/c}{0.194 + w/c}\right) \cdot \\ & \exp\left[-\left(\frac{\tau_T}{t}\right)^{\beta}\right] \cdot \frac{E}{R} \cdot \left(\frac{1}{273 + T_r} - \frac{1}{273 + T_c}\right) + \\ & k \cdot \nabla T + C_c \cdot \left\{\tau_y(t) + \left\{\mu_r \cdot \exp\left(\frac{E}{RT_{c0}}\right) + \right.\right. \\ & \left.\left.\left[1000 - \mu_r \cdot \exp\left(\frac{E}{RT_{c0}}\right)\right] \cdot \left(\frac{t}{t_v}\right)^n\right\} \cdot \dot{\gamma} + \rho_c g\right\} \cdot \nabla T = 0 \end{aligned} \tag{18}$$

This numerical model will be implemented into COMSOL Multiphysics to predict the coupled effect of cement hydration and temperature variation on the evolution of the rheological properties. The predicted results will be validated against the experimental outcomes that are demonstrated in the next section.

3 Experimental programs

3.1 Materials and apparatus

Silicate cement 325# was selected for preparing the fresh CTB slurry samples. The tailings used for the samples were from Baixiangshan Iron Mine in Anhui province, China, and transported to University of Science and Technology Beijing to conduct the laboratory tests. The particle size distribution of the tailings (Fig. 1) was determined with an electric wet sieve shaker. The laboratory rheological test was conducted with Brookfield R/S plus rheometer, which owns a temperature probe to investigate the temperature variation within the CTB slurry. The tested results were recorded by the rheometer and graphically shown on the computer screen. Table 2 illustrates the physical characteristics of the three sets of CTB slurry samples.

For the purpose of revealing the effect of cement hydration and temperature variation on the rheological properties of CTB, three additional sets of fresh tailings,

Table 2 General physical characteristics of fresh CTB slurry

Sample	Tailings density/ ($t\cdot m^{-3}$)	Mass fraction of solid/%	Initial temperature/°C	Cement to tailings ratio	Water to cement ratio	Slump/ cm
1#	2.63	66	21.5	1/8	4.6	20
2#	2.63	68	21.5	1/8	4.2	18
3#	2.63	70	21.5	1/8	3.9	16

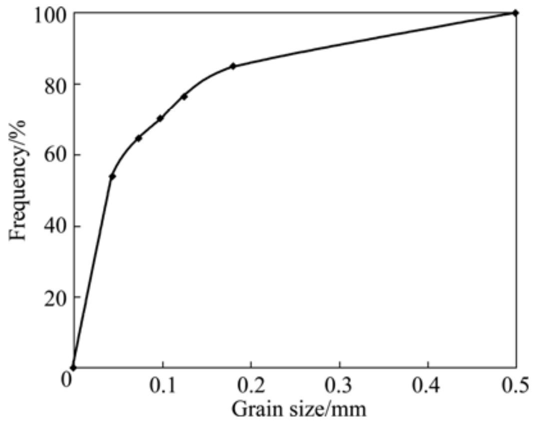

Fig. 1 Particle size distribution of tailings

backfill (TB) slurries (i.e., no cement addition), were chosen to conduct a contrastive experiment. Table 3 shows the mix proportion of the prepared fresh TB slurry.

Table 3 Mix proportion of fresh TB slurry

Sample	Tailings density/ ($t\cdot m^{-3}$)	Mass fraction of solid/%	Initial temperature/ °C	Slump/ cm
4#	2.63	66	21.5	20
5#	2.63	68	21.5	18
6#	2.63	70	21.5	16

3.2 Test results

For the sake of space, only two groups (TB and CTB slurries with a same solid mass fraction of 66%) of the tested results are graphically displayed in Figs. 2 and 3. The effects of various factors (cement hydration, initial CTB temperature, cement-to-tailings ratio, and water-to-cement ratio) on the rheological properties (viscosity and shear stress) of fresh TB and CTB slurries are demonstrated in Figs. 4−9, among which Figs. 5 and 6 illustrate the contrast of predicted results against tested ones. It should be specified that, every "viscosity" on the vertical axis (*Y*-axis) in the following figures (i.e., Figs. 2(a), Fig. 3(a), Fig. 4(a), Fig. 5, Fig. 7(a), Fig. 8(a), Fig. 9(a)) denotes the apparent viscosity of relevant slurries.

According to the results of Bingham regression analysis, the rheological model for 66% TB slurry can be written as the following form:

$$\tau_s = 142.09 + 0.82\dot{\gamma} \tag{19}$$

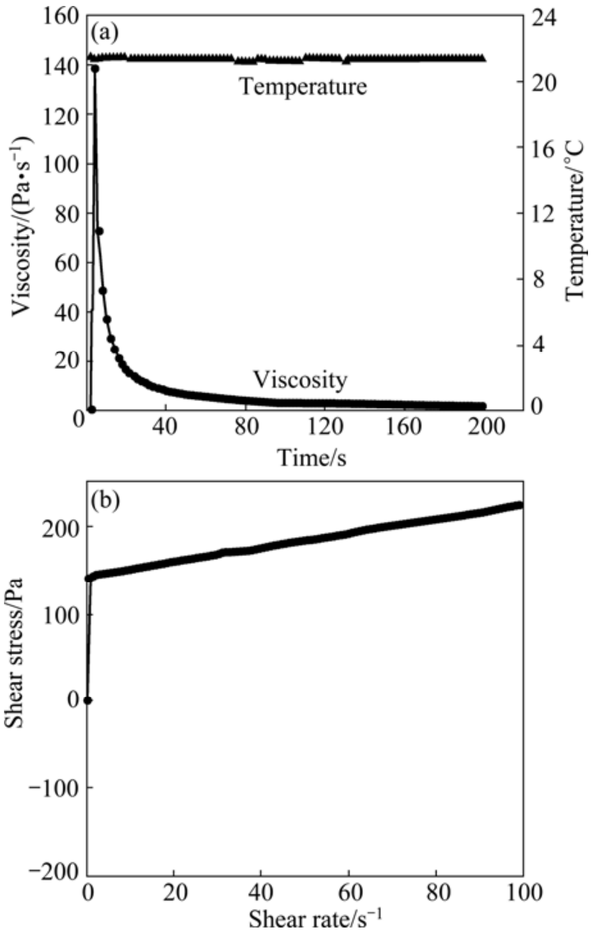

Fig. 2 Experimental results of fresh TB slurry: (a) Evolution of fresh TB slurry's viscosity versus time; (b) Bingham regression analysis of fresh TB slurry's shear stress versus shear rate

where τ_s is the shear stress of the fresh TB slurry, and its yield stress and Bingham plastic viscosity are 142.09 Pa and 0.82 Pa·s respectively; $\dot{\gamma}$ is the shear rate.

Similarly, the rheological model for 66% CTB slurry is

$$\tau_s = 393.2 + 0.79\dot{\gamma} \tag{20}$$

It should be pointed out that, the viscosity of 66% CTB slurry is expected to be greater than that of 66% TB slurry. However, the value of the former is 0.79 Pa·s, which is actually smaller than that of the latter (0.82 Pa·s). This may be due to the uncertain and varied boundary conditions when conducting the experiment in laboratory. Table 4 summaries the rheometer testing results of all the fresh TB and CTB slurry samples.

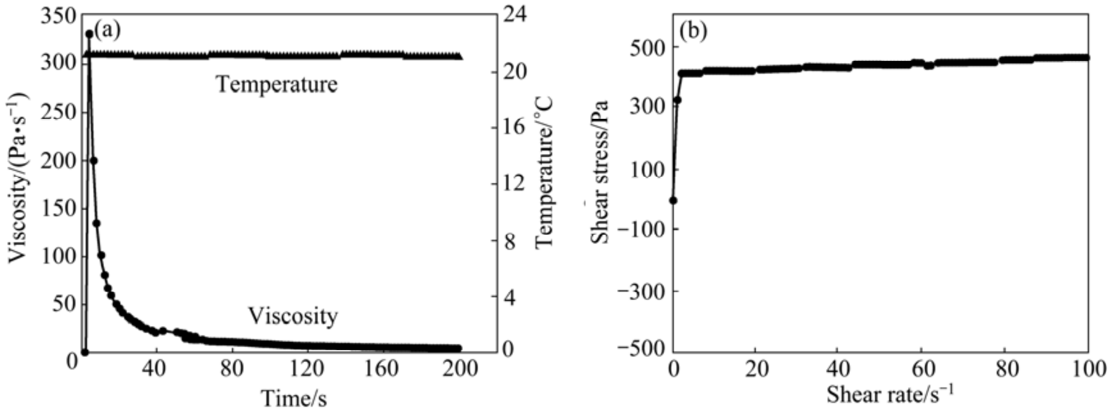

Fig. 3 Experimental results of fresh CTB slurry: (a) Evolution of fresh CTB slurry's viscosity versus time; (b) Bingham regression analysis of fresh CTB slurry's shear stress versus shear rate

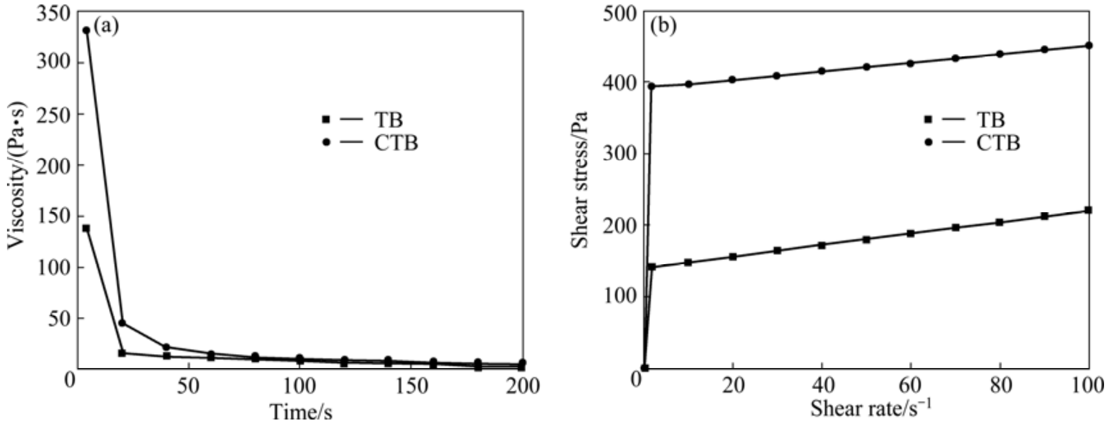

Fig. 4 Effect of cement hydration on fresh CTB slurry's rheological properties: (a) Viscosity versus time; (b) Shear stress versus shear rate

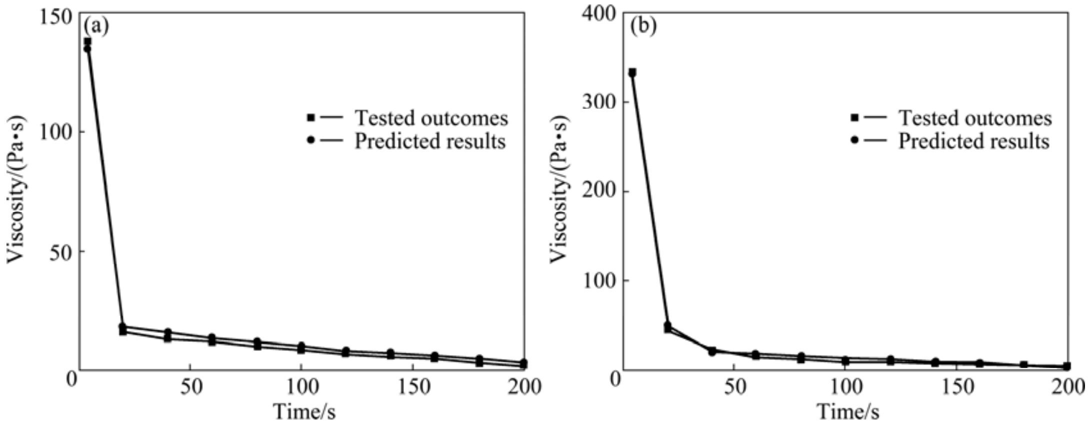

Fig. 5 Comparison of predicted and tested results of viscosity: (a) Fresh TB slurry; (b) Fresh CTB slurry

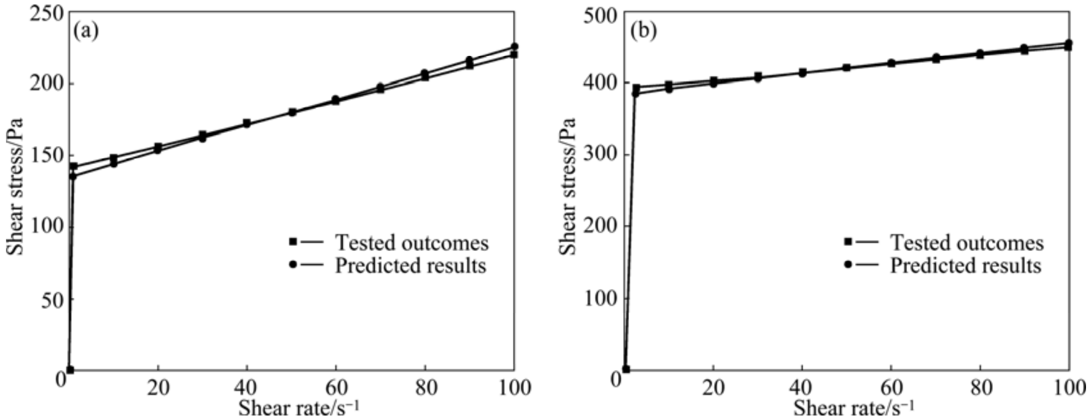

Fig. 6 Comparison of predicted and tested results of shear stress: (a) Fresh TB slurry; (b) Fresh CTB slurry

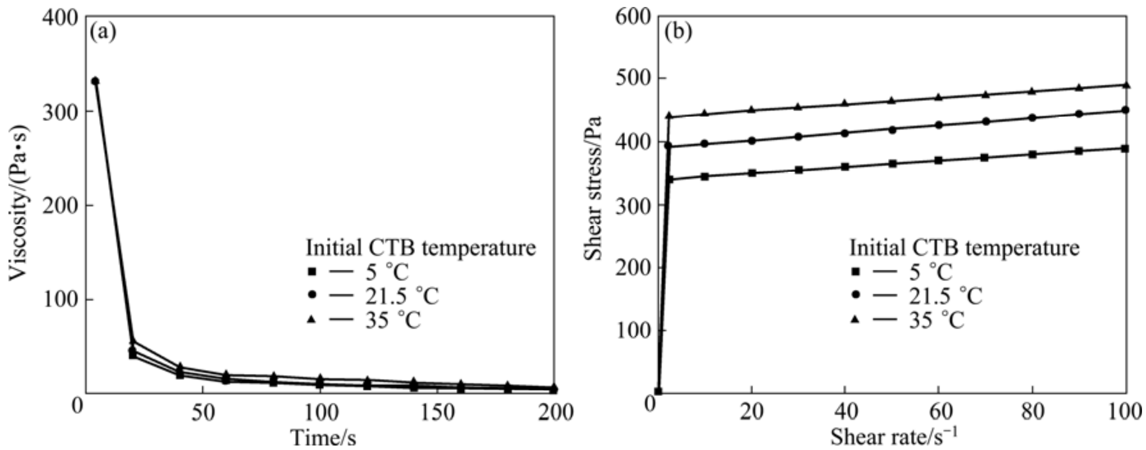

Fig. 7 Effect of initial CTB temperature on fresh CTB slurry's rheological properties: (a) Viscosity versus time; (b) Shear stress versus shear rate

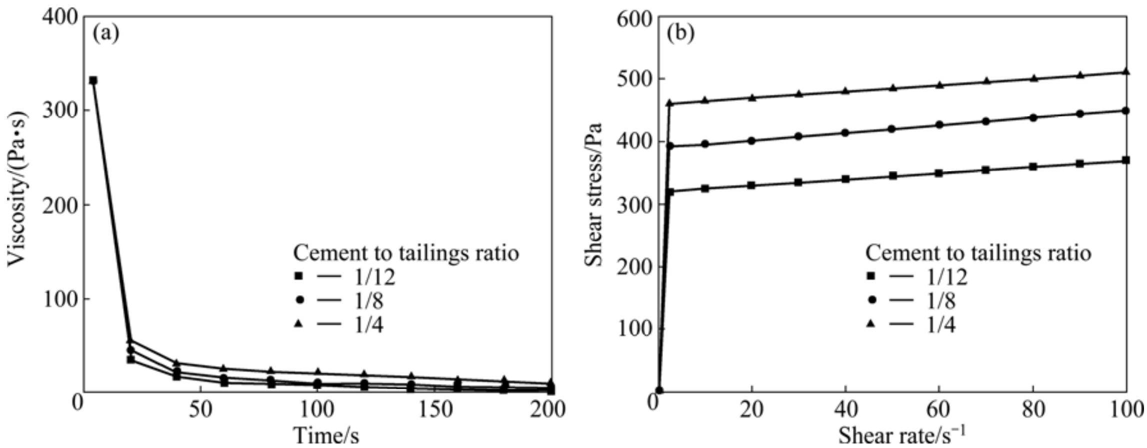

Fig. 8 Effect of cement-to-tailings ratio on fresh CTB slurry's rheological properties: (a) Viscosity versus time; (b) Shear stress versus shear rate

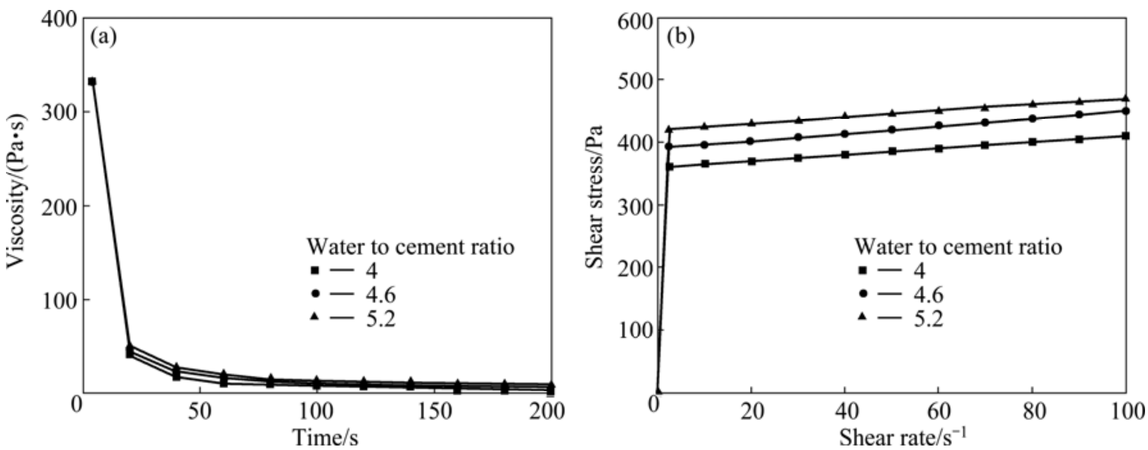

Fig. 9 Effect of water-to-cement ratio on fresh CTB slurry's rheological properties: (a) Viscosity versus time; (b) Shear stress versus shear rate

According to Table 4, for both fresh TB and CTB slurries, the higher the solid mass fraction is, the greater the Bingham plastic viscosity and yield stress are.

Experimentally, Fig. 4 demonstrates the effect of cement hydration on evolution of rheological properties (apparent viscosity, and shear stress) of the CTB mixtures (66% solid mass fraction) in contrast with that of the TB ones (66% solid mass fraction).

From Fig. 4, it can be observed that, compared with the fresh TB slurry, the addition of cement contributes to the significant increase of apparent viscosity and shear stress in the fresh CTB one.

Table 4 Summary of rheometer testing results

Experimental sample	Solid mass fraction/%	Cement to tailings ratio	Bingham plastic viscosity/ (Pa·s)	Yield stress/Pa
Fresh TB slurry	66	–	0.82	142.09
Fresh CTB slurry	66	1:8	0.79	393.20
Fresh TB slurry	68	–	1.02	286.06
Fresh CTB slurry	68	1:8	1.45	759.61
Fresh TB slurry	70	–	1.10	498.65
Fresh CTB slurry	70	1:8	1.83	1363.15

4 Validation and simulation

4.1 Model validation

The obtained experimental results from conducting on the fresh CTB and TB slurries with 66% solid mass fraction were employed to compare with the outcomes predicted by the developed numerical model. Figures 5(a) and (b) separately display the comparison of the predicted viscosity evolution of the fresh TB and CTB slurries with those of the experimental one. In a similar way, Fig. 6(a) and (b) respectively demonstrate the contrast between the predicted and tested evolution of the shear stress of the two kinds of slurries.

From Fig. 5, it can be discovered that, the predicted viscosity evolution is in good agreement with the experimental one for both fresh TB and CTB slurries. Similarly, Fig. 6 also shows a good agreement between the predicted and experimental shear stress evolution of the two types of slurries. Therefore, it can be concluded that the validity and applicability of the developed numerical model are testified. In addition, it can also be found both the predicted and tested results reveal that, the viscosities of the fresh TB and CTB slurries decrease with the development of elapsed time, and their shear stresses increase with the increase of shear rate.

4.2 Model application

As illustrated before, the developed numerical model is proved to be valid and available to study on the evolution of fresh CTB slurry's rheological properties. Correspondently, this numerical model is applied to further revealing the influence of different cement hydration and temperature conditions on the evolution of fresh CTB slurry's viscosity and shear stress. Table 5 gives the main input parameters for the model simulation. Figure 7 demonstrates the effect of various initial CTB temperatures on the evolution of fresh CTB slurry's rheological properties.

Table 5 Main input parameters for model application

Initial CTB temperature/ °C	Cement to tailings ratio	Water to cement ratio	Solid fraction by mass/%
5, 21.5, 35	1/8	4.6	66
21.5	1/12, 1/8, 1/4	4.6	66
21.5	1/8	4, 4.6, 5.2	66

R is 8.314 J/(mol·K)

According to Fig. 7, it can be observed that, both the viscosity and shear stress of the fresh CTB slurry increase with the rise of initial CTB temperatures. This is due to the reason that raising the initial CTB temperature can significantly accelerate the cement hydration progress, which is in great favor of generating more hydration products. As a result, these hydration products precipitate to increase the viscosity and shear stress by raising the interactive frictional resistance of the cemented particle aggregate within the fresh CTB mixtures.

In addition to the higher initial CTB temperatures giving rise to more hydration products, raising the initial CTB temperatures can also speed up the cement hydration process to consume more water, which in turn leads to the increase of solid fraction of the CTB mixtures. Consequently, the viscosity and shear stress of the fresh CTB slurry would be correspondingly increased. This argument can be verified by the experimentally revealed results in Table 4.

The outcomes demonstrated by Fig. 7 are significantly meaningful to preparing CTB mixtures in practice. As it has been discussed above, the friction between CTB mixtures and inner wall of the transporting pipeline would generate certain amount of heat, resulting in the temperature rise of CTB mixtures. In addition, with the deepening of mining depth, the factor of the geothermic gradient would also contribute to increasing the initial CTB temperature. As a result, the values of fresh CTB slurry's viscosity and shear stress increase because of its temperature rise. This is unfavorable to the transportation of CTB mixtures. Therefore, some necessary solutions could be adopted to avoid these disadvantages in practice. For instance, friction-reducing additives can be added into the CTB slurry to improve its flowability. For another example, the underground ventilation facilities can be improved to control the thermal conditions in deep mine, which may modify the

CTB slurry's fluidity and thus avoid the pipe plugging induced by high temperature.

The effect of different cement-to-tailings ratios on the rheological properties of fresh CTB slurry is illustrated by Fig. 8. From this figure, it can be discovered that, raising the cement-to-tailings ratio can increase the viscosity and shear stress of the fresh CTB slurry. This is because higher cement-to-tailings ratio represents that larger amount of cement is utilized to prepare the fresh CTB mixtures. On one hand, larger amount of heat is produced, which causes higher temperature development within the fresh CTB slurry. This temperature rise in return promotes the cement hydration progress. This is how the cement hydration and its accompanying thermal process are interacted with each other. On the other hand, more hydration products are generated and more water is consumed. Consequently, the precipitation and accumulation of the hydration products contribute to the increase of the slurry's viscosity and shear stress through enhancing the interactional frictional force among the cemented particle aggregates within CTB mixtures [19]. Meanwhile, the increase in the solid mass fraction of fresh CTB slurry also contributes to increasing its viscosity and shear stress.

The implication for practical preparation of fresh CTB slurry can be elaborated as follows. There is a competition between the cement dosage for fresh CTB slurries and that for hardened CTB structures formed by these slurries. On one hand, it should be ensured that the cement content is sufficient enough for the stable CTB structures to support the ground and stope. On the other hand, if the cement dosage is too much, according to the illustrated results in Fig. 8, the viscosity and shear stress of the fresh CTB slurry would be relatively high, which is not favorable for transporting this slurry. Therefore, it is essential and significant to find a good balance between the UCS of CTB structures and the flowability of CTB slurries by means of achieving suitable cement content.

Figure 9 demonstrates the influence of diverse water-to-cement ratios on the rheological behavior of fresh CTB slurry. On the basis of this graph, it can be obviously discovered that, a higher value of water-to-cement ratio results in the increase of fresh CTB slurry's viscosity and shear stress. This is attributed to the fact that the simulation is conducted by the developed numerical model. As discussed above, when the value of water-to-cement ratio (w/c) is lower than 6.258, raising the value of w/c can accelerate the rate of cement hydration. That is to say, higher w/c value implies stronger cement hydration process, which generates larger amount of hydration product to raise the viscosity and shear stress of fresh CTB slurry. Nevertheless, it should be stated that if the w/c value is higher than 6.258, the effect of various water-to-cement ratios on the evolution of fresh CTB slurry's rheological properties needs to be studied by further experimental researches.

5 Conclusions

1) Through coupling the cement hydration, heat transfer and fluid rheology equations, a numerical model was developed for studying the coupled effect of cement hydration and temperature on the rheological properties of fresh CTB slurry. In order to prove the validity and applicability of this developed model, a laboratory rheometer test was conducted to produce the outcomes for the purpose of contrast and validation. This test showed that the model prediction was in full agreement with the experimental results.

2) The coupled model was utilized to carry out several simulation applications, and the following conclusions can be made: raising the initial CTB temperature, cement-to-tailings ratio and water-to-cement ratio can significantly increase the viscosity and shear stress of the fresh CTB slurry.

3) The results illustrated by model simulation are helpful for understanding the rheological behavior of the fresh CTB slurry under the coupled effect of cement hydration and temperature, thus providing practical benefits for the preparation of CTB mixtures. For instance, the transporting of the fresh CTB slurry can be promoted by optimizing its mix proportion. In addition, the developed model also provides an effective numerical tool for studying the rheological properties of fresh CTB slurry.

References

[1] WU D, FALL M, CAI S. Coupled modeling of temperature distribution and evolution in cemented tailings backfill structures that contain mineral admixtures [J]. Geotechnical and Geological Engineering, 2012, 30(4): 935−961.

[2] OREJARENA L, FALL M. Artificial neural network based modeling of the coupled effect of sulphate and temperature on the strength of cemented paste backfill [J]. Canadian Journal of Civil Engineering, 2011, 38(1): 100−109.

[3] KLEIN K A, SIMON D. Effect of specimen composition on the strength development in cemented paste backfill [J]. Canadian Geotechnical Journal, 2006, 43: 310−324.

[4] NGUYEN Q D, BOGER D V. Application of rheology to solving tailings disposal problems [J]. International Journal of Mineral Processing, 1998, 54(3−4): 217−233.

[5] PETIT J Y, WIRQUIN E, KHAYAT K H. Coupled effect of time and temperature on variations of plastic viscosity of highly flowable mortar [J]. Cement and Concrete Research, 2010, 32(1): 43−53.

[6] NASIR O, FALL M. Coupling binder hydration, temperature and compressive strength development of underground cemented paste backfill at early ages [J]. Tunneling and Underground Space Technology, 2010, 25(1): 9−20.

[7] NASIR O, FALL M. Modeling the heat development in hydrating CPB structures [J]. Computer and Geotechnics, 2009, 36(7): 1207−1218.

[8] COMSOL A B. COMSOL Multiphysics user's guide [EB/OL]. 2005. http://www.comsol.com/.

[9] de SCHUTTER G. Hydration and temperature development of concrete made with blast-furnace slag cement [J]. Cement and Concrete Research, 1999, 29(1): 143−149.

[10] SCHINDLER A K. Effect of temperature on the hydration of cementitious materials [J]. ACI Materials Journal, 2004, 101(1): 72−81.

[11] SCHINDLER A K, FOLLIARD K J. Heat of hydration models for cementitious materials [J]. ACI Materials Journal, 2005, 102(1): 24−33.

[12] KJELLSEN K O, DETWILER R J, GJØRV O E. Development of microstructure in plain cement pastes hydrated at different temperatures [J]. Cement and Concrete Research, 1991, 21(1): 179−189.

[13] KIM J K, HAN S H, LEE K M. Estimation of compressive strength by a new apparent activation energy function [J]. Cement and Concrete Research, 2001, 31(2): 217−225.

[14] CELESTIN J, FALL M. Thermal conductivity of cemented paste backfill material and factors affecting it [J]. International Journal of Mining, Reclamation and Environment, 2009, 23(4): 274−290.

[15] WU D, FALL M, CAI S. Coupling temperature, cement hydration and rheological behaviour of fresh cemented paste backfill [J]. Minerals Engineering, 2013, 42: 76−87.

[16] PETIT J Y, KHAYAT K H, WIRQUIN E. Coupled effect of time and temperature on variations of plastic viscosity of highly flowable mortar [J]. Cement and Concrete Research, 2009, 39(3): 165−170.

[17] PAPO A, CAUFIN B. A study of the hydration process of cement pastes by means of oscillatory rheological techniques [J]. Cement and Concrete Research, 1991, 21(6): 1111−1117.

[18] PETIT J Y, KHAYAT K H, WIRQUIN E. Coupled effect of time and temperature on variation of yield value of highly flowable micromortars [J]. Cement and Concrete Research, 2006, 36(5): 832−841.

[19] NEHDI M, AL-MARTINI S. Coupled effects of high temperature, prolonged mixing time, and chemical admixtures on rheology of fresh concrete [J]. ACI Materials Journal, 2009, 106(3): 1−10.

水化反应和温度对新鲜胶结尾砂充填料浆流变特性的耦合效应

吴 迪[1,2]，蔡嗣经[3]，黄 刚[3]

1. 中国矿业大学(北京) 资源与安全工程学院，北京 100083；

2. 中国矿业大学(北京) 煤炭资源与安全开采国家重点实验室，北京 100083；

3. 北京科技大学 土木与环境工程学院，北京 100083

摘 要：新鲜胶结尾砂充填料浆的流动性取决于它的流变特性，所以理解新鲜料浆的流变性具有重要的意义。此外，料浆的流变性又与料浆中所发生的水泥水化反应进程和温度的发展变化相关。基于此原因，建立数值模型以分析和预测在水化反应和温度耦合作用下充填料浆流变特性的演化规律。在实验室通过试验研究了料浆的流变行为，并将试验结果与模拟结果进行对比来验证模型的有效性。在不同的条件(料浆的初始温度、灰砂比、水灰比)下，利用所建立的模型对水化反应和温度耦合效应下的料浆流变规律进行模拟研究。研究结果有助于更好地理解胶结尾砂充填料浆的流变性。

关键词：胶结尾砂充填；水化反应；温度；流变；耦合模型

(Edited by Hua YANG)