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Research Article

Investigating the Effect of Solid Components on Yield Stress for Cemented Paste Backfill via Uniform Design

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Cemented paste backfill (CPB) technology has been applied quite popular around the world. Yield stress is a key factor determining whether CPB could be transported. In order to reveal the effect of solid components on yield stress of CPB, a uniform design experimental program (four factors and six levels) was conducted to test the rheological property of a mine's CPB. The tested four factors including mass fraction, cement versus other solids ratio, coarse tailings, and gravel contents were considered during the experiment design. Likewise, six experimental levels were given to each factor. Results of the test show that yield stress increased with the mass fraction and cement content. However, the trend reversed for the content of coarse tailings and gravel. Contribution of the four factors to yield stress in descending order is mass fraction > content of gravel > content of coarse tailings > cement versus other tailings ration. Effect of solid components on the yield stress of CPB is mainly due to the different flocculation structure inside the CPB. These various flow structures result in the different free-water content of CPB, leading to a different yield stress value.

1. Introduction

Cemented paste backfill (CPB) technology applies the mixture of thickened tailings, coarse aggregate, cement, and other binders and transports it into underground deposits with pump or self-gravity [1, 2]. This technology has been a quite popular method around the world on account of its higher solid fraction in suspension in comparison with other backfill methods [3–6]. However, higher solid fraction of suspension also demands higher pipeline transport technology, which is a key factor determining whether CPB could be applied widely. In general, aggregate or smelting slag is available to reduce the resistance of paste transportation. Furthermore, the strength of backfill body also increases with the addition of coarse aggregate or smelting slag [7].

Yield stress is considered as the key parameter to assess the rheology for a wide range of suspension. It is applied in food, medicine, printing, pottery, and mining industries [8]. There are abundant standards to assess the flowability of paste, whereas yield stress is a quite important parameter. Firstly, yield stress is closely related with every section of CPB technology like thickening, mixing, and transportation. Secondly, yield stress can comprehensively reflect the flowability of paste and hence becomes the key parameter in design of paste pipeline transportation. Thirdly, the measurement of yield stress shows an excellent repeatability. This means the possibility of comparison between different kinds of materials, provided the same measurement method is applied.

There are many factors that can determine the yield stress. Many studies in last decades concentrate a lot on factors influencing yield stress for thickened or paste tailings. Some studies proposed that the yield stress of thickened tailings is related with grinding fineness [9]. The effect of additives such as limestone on the rheology was also mentioned [10]. At the same time, others indicated that the yield stress of thickened tailings is closely related with physical properties (solid fraction, particle gradient, and particle shape), intergranular forces (type and value), chemical and physical properties of cement, inner structure, physical aging, and other factors [11–18]. For CPB technology, aggregate composition usually means the mixture of tailings, coarse aggregate, binders, and water. The change of rheological properties of paste materials caused by addition of aggregates is decisive to determine the paste pipeline transportation. Therefore, it is also essentially considered in design of paste composition and transport system.

Therefore, a uniform design experiment, in which solid fraction, coarse aggregate concentration, coarse sand concentration, and cement content are considered as key factors, is carried out in this paper. The mechanism that how aggregates influence the yield stress of paste is studied in order to offer a reference for paste backfill technology.

2. Materials and Methods

2.1. Experimental Materials. Several aggregates that are mostly employed in CPB technology are selected as experimental samples, including unclassified tailings, cement, gravel, and coarse sand. The true density of unclassified tailings is 2.75 g/cm^3, and corresponding bulk density is 1.75 g/cm^3. The true solid densities of the tailings were determined via (1) based on the specific gravity test results. The specific gravity (G_s) of the two tailings was obtained by applying a water pycnometer as per method ASTM D854.

$$\rho_s = G_s \rho_w, \quad (1)$$

where G_s is the specific gravity of dry tailings, ρ_s is the true solid density of dry tailings, and ρ_w is the density of water at 20°C. It should be noted that the G_s is a dimensionless parameter in consideration that same units are used for the densities. The bulk density of tailings was calculated as per standard GB/T 14684-2001 (6.14.2.3). A cylinder was filled with dry tailings at a known mass and covered with a rubber flat surface. The cylinder was tapped until no change in volume of the tailings occurs. The bulk densities of the tailings were referred to the ratio of the mass of the tailings to the volume of the cylinder.

The average particle size is 75.59 μm, and medium particle size is 34.95 μm. The accumulated content of particles under 20 μm is 37.20%. The 32.5 R Portland cement is applied in this experiment. The true density of cement is 3.05 g/cm^3, and the bulk density is 1.10 g/cm^3. The coarse sand is taken from surface tailing pond. Due to natural settlement, the coarse sand is coarser than total tailings. The particle size distribution (PSD) of total tailing samples was determined using a Malvern laser mastersizer 2000 (Malvern Instruments, Ltd., Worcestershire, UK), which measures particle size in the range of 0.02–2000 μm with an accuracy of ±1%. The coarse sand size and gravel particle size were measured by artificial sieving methods. The physical properties (e.g., true density, bulk density, and PSD) were provided by the Zheba Cement Co., Ltd., from Yunnan province, China. The particle size distribution of unclassified tailings, aggregate, and cement is shown in Figure 1. From coarse to fine, the aggregates are gravel, coarse sand, total tailings, and cement, respectively.

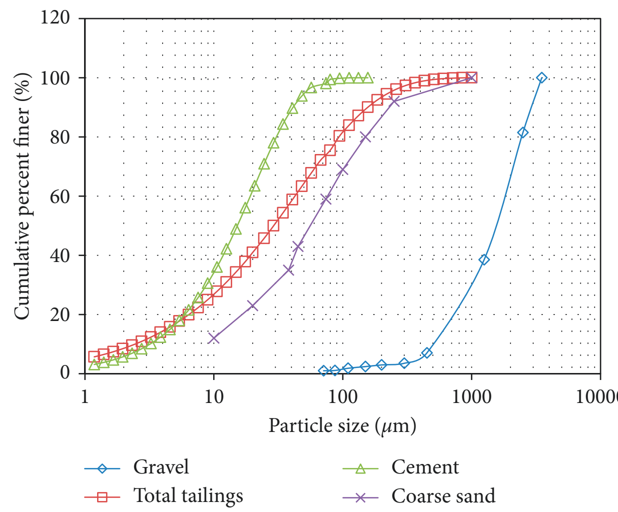

Figure 1: The particle size distribution of gravel, coarse sand, total tailings, and cement.

2.2. Testing Method. A scientific uniform design method (4 factors and 6 levels) is applied in the experiment. 4 factors include mass fraction, ratio of cement versus other solids, content of coarse sand, and gravel. Furthermore, mass fraction changes between 79.0% and 81.5% (79.0%, 79.5%, 80.0%, 80.5%, 81%, and 81.5%), and ratio of cement versus other solids changes between 1 : 6 and 1 : 11 (1 : 6, 1 : 7, 1 : 8, 1 : 9, 1 : 10, and 1 : 11). Besides, the content of coarse sand changes between 1% and 16% (1%, 4%, 7%, 10%, 13%, and 16%), and the content of gravel changes between 1% and 16% (1%, 4%, 7%, 10%, 13%, and 16%). Following items are considered in the selection of levels: (1) higher mass fraction can prevent settling of aggregates for gravity, which is beneficial to obtain accurate results; (2) the ratio of cement versus other solids, content of coarse sand, and content of gravel are based on the practical CPB application situation of China mines; and (3) higher ratio of tailings versus cement could decrease the content of cement, and higher proportion of coarse sand and gravel means higher waste utilization ratio.

Three sets of experiments (B1, B2, and B3) are carried out simultaneously to verify the accuracy of experimental results. According to the requirement from measurement of yield stress, the overall mass of each set of sample is 900 g. The uniform design and controlled trials are shown in Table 1 [19].

The Brookfield R/S cross-blade rheometer is applied in the experiment. The rotator is immersed into suspension. At the same time, the sensors measuring the torque of rotator are linked to the rotator. The rotator could rotate with a wide range of speed. The shear stress-shear rate curve can be recorded and analyzed in the software interface of RHEO 3000. The diameter and height of rotator is 20 mm and 40 mm, respectively. The direct method is applied in measurement for higher accuracy of measured yield stress.

Table 1: Uniform design experiments $U_6^*(6^4)$ program (deviation coefficient $D = 0.4570$).

Type	Level	Mass fraction (%)	Ratio of cement versus solids	Coarse sand (%)	Gravel (%)
Uniform design	A1	79.0 (1)	1 : 7 (2)	7 (3)	16 (6)
	A2	79.5 (2)	1 : 9 (4)	16 (6)	13 (5)
	A3	80.0 (3)	1 : 11 (6)	4 (2)	10 (4)
	A4	80.5 (4)	1 : 6 (1)	13 (5)	7 (3)
	A5	81.0 (5)	1 : 8 (3)	1 (1)	4 (2)
	A6	81.5 (6)	1 : 10 (5)	10 (4)	1 (1)
Controlled trials	B1	80.0	1 : 8	0	0
	B2	80.0	1 : 8	14	0
	B3	80.0	1 : 8	0	14

Note: in this paper, the ratio of cement versus solids means cement versus sum of unclassified tailings, gravel, and coarse sand. The content of coarse sand means its proportion in overall materials. The content of gravel means its proportion in overall materials as well.

Hence, the CSS mode is selected in the experiment and corresponding parameters are set up.

3. Results and Discussion

3.1. Evolution of Shear Stress-Shear Rate Curve and Herschel–Bulkley Yield Stress Regression. The curve of shear stress versus shear rate is shown in Figure 2. It can be seen that yield phenomenon occurs when shear stress reaches certain value for each sample. Because the higher mass fraction of paste is considered as non-Newtonian fluid, the rotator would not rotate unless stress exceeds the critical shear stress. Several factors are investigated in the experiment with uniform design. Therefore, the experimental curve in Figure 2 is not available for direct comparison and analysis. Regression of yield stress for each set of experiment is essential for the establishment of functional relationship between yield stress and other related factors.

The regression of shear stress-shear rate curve is carried out firstly. In general, the most used rheological models for paste are Bingham model (2 parameters) and Herschel–Bulkley model (3 parameters). The Herschel–Bulkley (H-B) model shows more accuracy than the Bingham model and gets applied more widely [20–22]. Hence, the H-B model is used to carry out the regression of yield stress. The H-B model is shown as below:

$$\tau = \tau_0 + \eta\gamma^n, \tag{2}$$

where τ is the shear stress (Pa); τ_0 is the yield stress (Pa); η is the coefficient of stiffness (Pa·s); γ is the shear rate (s^{-1}); and n is the flow performance index.

On the basis of experimental results, the regression of yield stress for suspension in different levels is carried out by H-B model. Regression results show that the complex correlation coefficients R^2 are between 0.957 and 0.994, which indicates an excellent regression. The regression results of yield stress are shown in Figure 3.

3.2. Effect of Solid Components on Yield Stress of CPB. Based on Figure 3, the regression between yield stress and related factors for paste is carried out by uniform design software. Then, the proposed regression equation is shown below:

$$\begin{aligned} y = {} & -2.32 \times 10^{20} \times 0.6^{x_1} - 3.8 \times 10^3 x_2^{-2} + 38 \ln x_3 \\ & + 3.1 \times 10^{-3} \times (-2)^{x_4} + 629, \end{aligned} \tag{3}$$

where y is the yield stress (Pa); x_1 is the mass fraction of suspension (%); x_2 is the ratio of cement versus other solids (%); x_3 is the content of coarse sand (%); and x_4 is the content of gravel (%).

According to (3), yield stress shows a positive correlation with mass fraction and ratio of cement versus other solids. Besides, yield stress shows a negative correlation with the content of gravel or coarse sand (the significant level $\alpha = 0.05$, the inspection value $F_t = 2.973e + 4$, and the critical value $F_{(0.05,4,1)} = 224.6$, $F_t > F_{(0.05,4,1)}$), and an excellent regression is shown. The complex correlation coefficient $R^2 = 0.999$.

Contributions of each factor in the regression equation are given below, which are arranged by the descending of partial regression square sum.

$$\begin{aligned} & U_{(1)} = 7.22e + 4, \\ & \frac{U_{(1)}}{U} = 81.1\%, \\ & U_{(4)} = 1.48e + 4, \\ & \frac{U_{(4)}}{U} = 16.6\%, \\ & U_{(3)} = 5.84e + 3, \\ & \frac{U_{(3)}}{U} = 6.56\%, \\ & U_{(2)} = 3.18e + 3, \\ & \frac{U_{(2)}}{U} = 3.57\%. \end{aligned} \tag{4}$$

The contribution from the second factor x_2 (ratio of cement versus other solids) of equation is the lowest. Hence,

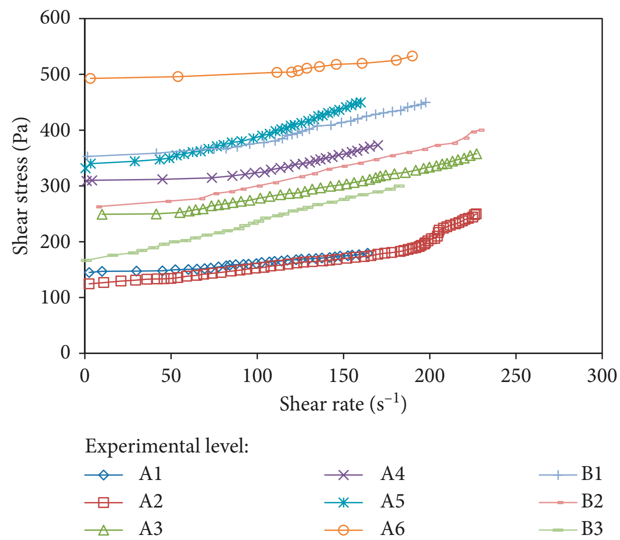

Figure 2: Curves of shear rate versus shear stress in each test.

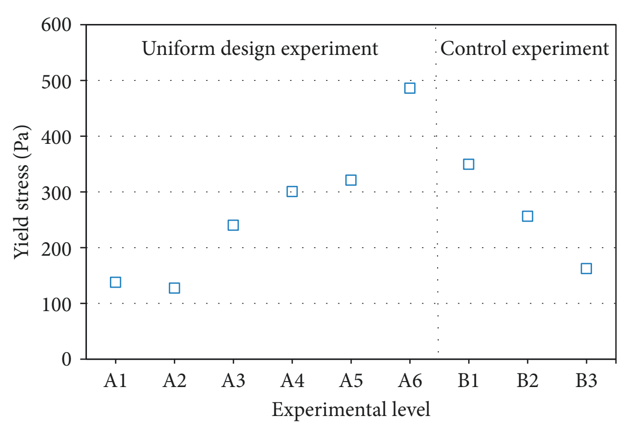

Figure 3: Regression results of the yield stress of paste in the experiment via the H-B model.

a significant test is performed. The inspection value $F_{(2)} = 4251$, the critical value $F_{(0.05,1,1)} = 161.4$, and $F_{(2)} > F_{(0.05,1,1)}$. It is clear that the equation shows an excellent correlation.

Based on the regression, the mass fraction of suspension is the key contribution and has the highest sensibility. Gravel is lower than the former mass fraction. Content of coarse sand and cement versus other solids ratio are the lowest. It should be noted that the measure yield stress in several sets of experiments fluctuates radically even though the mass fraction increases with a gradient of 0.5%. Furthermore, the yield stress fluctuates during 127.3 Pa~485.9 Pa when mass fraction changes between 79% and 81.5%. This means that yield stress triples when mass fraction increases the percentage of 2.5%. Except the impact from solid components, high mass fraction imposes the sensible fluctuation of yield stress, even an exponential increase [22, 23]. Hence, besides the pursuing of mass fraction during the CPB application, the transport performance should be paid more attention as well, because even a slight change of mass fraction may induce a significant increase of transport resistance.

The controlled trials indicate that the yield stress of paste is 349.46 Pa when solid mass fraction is 80% and the ratio of cement versus other solids is 1 : 8, without adding coarse sand and gravel. When 14% coarse sand is added, the yield stress of paste is 256.20 Pa, which is 26.69% less than that without adding coarse sand. If 14% gravel is added, the yield stress of paste is 162.36 Pa, dropping off as 53.54% in comparison with that without adding gravel materials. Therefore, the addition of coarse sand or gravel can impose the decline of yield stress of paste at same mass fraction and ratio of cement versus other solids. Besides, when the size of aggregates increases, the yield stress would decrease more significantly. This result is in agreement with the conclusion of uniform design experiments, which indicates that the content of coarse sand or gravel has a negative correlation with yield stress.

3.3. Analysis of Influence Mechanism of Solid Components on Yield Stress of Paste. Some studies indicate that surface of fine particle shows the significant physicochemistry effect,

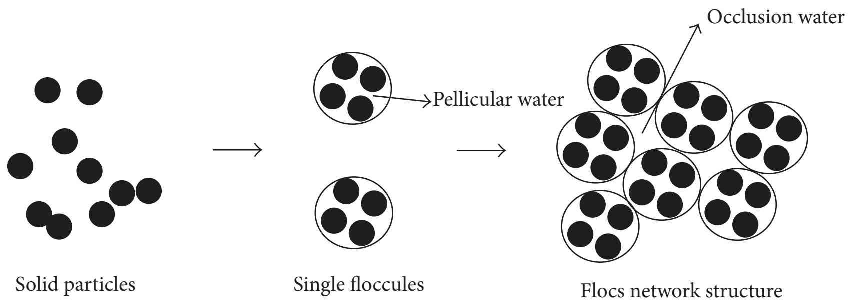

Figure 4: Water distribution in the flocculation structure of pastes.

which imposes the behavior of flocculation [24]. In terms of paste suspension, its internal structure consists of solid particles, pellicular water, occlusion water in flocs, and free water. The water distribution in paste suspension is shown in Figure 4.

Furthermore, pellicular water and occlusion water lose the capability of free-flow, which can be treated as solid matter. Whereas, the content of free water is the key cause that imposes the fluctuation of suspension flow ability. If no free water exists in paste materials, which means paste suspension consists of solid particles, pellicular water, and occlusion water in flocs, then the mass fraction of paste is the so-called limit mass fraction of paste, and C_{vm}. C_{vm} is a coupling parameter that characterizes the impact from particle gradient, content of fine particles, mineral composition, and shape and other factors, as shown in the following equation [24]:

$$C_{\mathrm{vm}} = \frac{1}{1 + 6\sum (P_i/\mathrm{d_i})(\delta + \beta)}, \quad (5)$$

where δ is the thickness of pellicular water, β is the thickness of occlusion water in flocs, and $6\sum (P_i/\mathrm{d_i})$ is the specific surface area of tailings particles.

Assume that volume fraction of paste is C_{v}, then overall volume of paste suspension consists of volume fraction of paste C_{v} and volume fraction of non-free water (pellicular water and occlusion water in flocs) $C_{\mathrm{v}}6\sum (P_i/\mathrm{d_i})(\delta + \beta)$.

Then, the volume fraction of solid matter in paste is

$$\begin{aligned} C'_{\mathrm{v}} &= C_{\mathrm{v}} + C_{\mathrm{v}}6\sum \frac{P_i}{d_i}(\delta + \beta) \\ &= C_{\mathrm{v}}\left[1 + 6\sum \frac{P_i}{d_i}(\delta + \beta)\right] = \frac{C_{\mathrm{v}}}{C_{\mathrm{vm}}}, \end{aligned} \quad (6)$$

where C'_{v} is a dimensionless quality, then

$$1 - C'_{\mathrm{v}} = 1 - \left(\frac{C_{\mathrm{v}}}{C_{\mathrm{vm}}}\right) \quad (7)$$

Equation (7) indicates the volume fraction of free water in paste suspension. According to (5)–(7), the impact of each factor on yield stress is analyzed as below:

(i) *Mass Fraction*. Given same particle gradient, which means same specific surface area, higher solid mass fraction imposes lower content of free water. Then, the structural strength of flocs increases and the trend that net structure forms increases as well. Therefore, yield stress shows a positive correlation with solid mass fraction.

(ii) *Ratio of Cement versus Other Solids*. The increase of cement content can consume some water in suspension for hydration reaction, which also increases the effective mass fraction of paste, imposing the increase of yield stress. Furthermore, abundant cement could promote the formation of flocs in suspension, which subsequently causes the increase of yield stress of paste. Hence, higher dosage of cement means higher yield stress. The content of cement has a positive correlation with the ratio of cement versus other solids.

(iii) *Coarse Sand and Gravel*. The size of coarse sand is situated between unclassified tailings and gravel. Therefore, unclassified tailings can be called as coarse tailings in comparison with other two materials. When coarse particles are added into the suspension, for the weak surface physic chemistry effect caused by bigger size, the pellicular water would decrease, and the effect that causes the formation of flocculation weakens. Then, the occlusion water in flocs decreases. This means that both δ and β decrease. According to the formula, the content of free water would increase. Therefore, yield stress decreases. The yield stress has a negative correlation with the content of coarse sand or gravel.

According to the previous analysis, impacts of mass fraction, ratio of cement versus other solids, content of coarse sand, and content of gravel on yield stress of paste can be induced like Figure 5. Whatever factor it is, its impact on yield stress is attributed to the influence on flow structure or flocculation structure in paste suspension, which would change the content of free water in paste suspension.

4. Conclusions

This study attempted to advance our understanding on factors influencing the yield stress of CPB (i.e., solid mass fraction, cement versus other solids ratio, coarse sand, and gravel content). Also, contribution of each factor and its

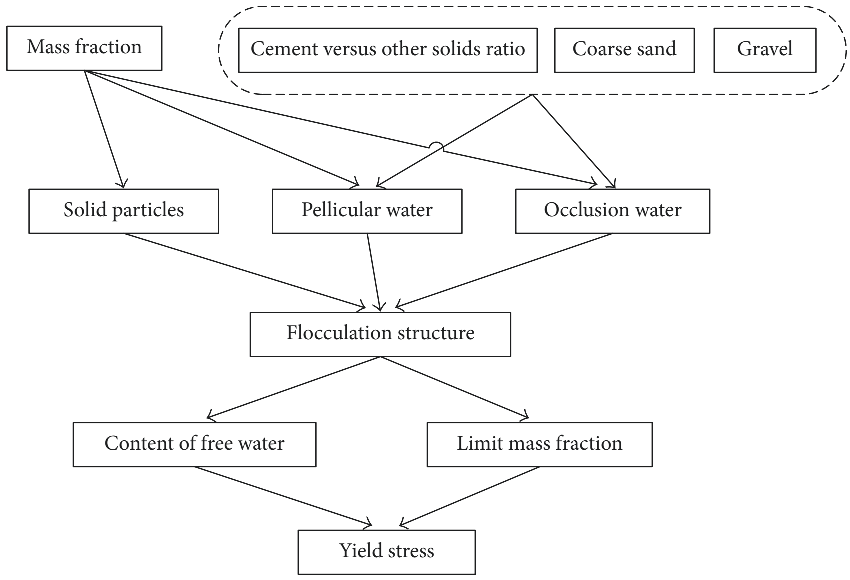

Figure 5: The network diagram of impacts of mass fraction, ratio of cement versus other solids, coarse sand, and gravel on yield stress of pastes.

influence mechanism is analyzed. The main conclusions derived from this study are summarized as follows:

(1) Experimental factors consist of mass fraction, ratio of cement versus other solids, content of gravel, and content of coarse sand. A uniform design experiment (4 factors and 6 levels) was carried out. The results indicate that yield stress has a positive correlation with mass fraction and ratio of cement versus other solids of paste. Besides, yield stress shows a negative correlation with content of gravel and coarse sand. Furthermore, mass fraction of suspension is the key contributor for yield stress. Gravel shows less effect on yield stress comparing with mass fraction. Content of coarse sand and ratio of cement versus other solids are the weakest.

(2) The influence of solid components on the yield stress of paste was evaluated by analyzing flocculation structure and flow structure. It is proposed that yield stress of paste is related with free water in suspension and limit mass fraction. Besides, the limit mass fraction can characterize the impact from particle gradient, fine particle content, mineral composition, shape, and other factors.

(3) The influence mechanisms of mass fraction, ratio of cement versus other solids, coarse sand, and gravel on yield stress are classified. The change of mass fraction influences the content of free water in paste suspension, which subsequently influences the strength of net structures between particles. The increase of cement would impose the increase of specific surface area of aggregates and formation of flocculation structure in paste, which subsequently causes the increase of yield stress of paste. The coarse sand and gravel influence the yield stress for changing the size of particles. When the size of particles becomes bigger, the volume of pellicular water or occlusion water in flocs tends to be smaller. Then, the proportion of free water increased, which causes the decrease of yield stress.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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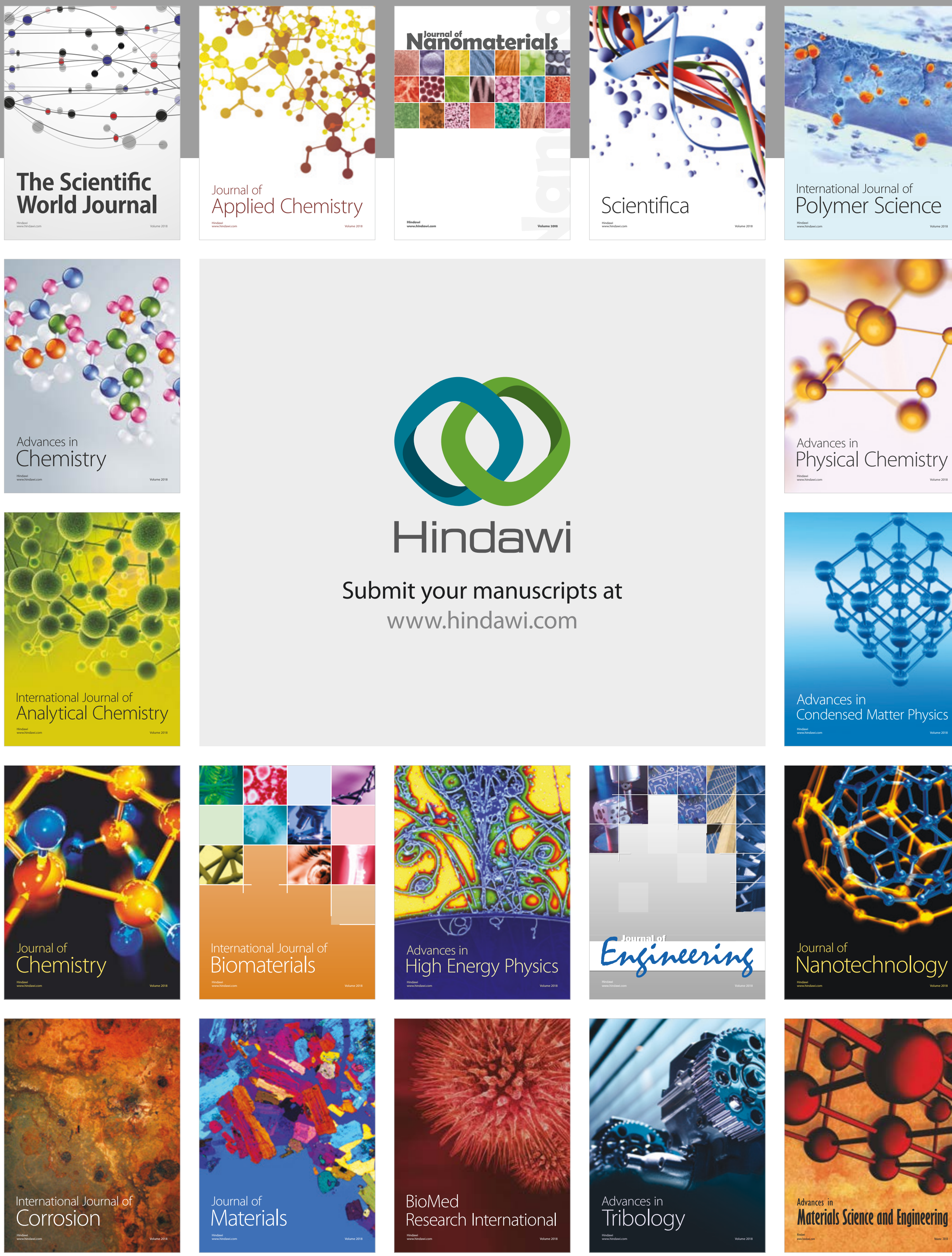

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