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# Preparation of coal slurry with 2-propanol

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**Abstract**

This study explored the feasibility of using waste organic solvents as substitutes for water to prepare coal slurries. The rheological properties of coal–2-propanol slurries were examined and compared with that of coal–water slurry (CWS). The good compatibility between coal particles and 2-propanol resulted in stable particle suspension in slurry which usually exhibit Newtonian behaviour. However, coal–2-propanol slurries usually shown higher viscosities comparing to CWSs at a fixed solid loading due to swelling of coal by 2-propanol. In addition, coal–2-propanol slurries demonstrated lower settling rates (higher stability) compared to CWSs presumably due to good compatibility between coal particles and 2-propanol. Finally, coal–2-propanol slurries formed bulky sediment with loose structure even coal particles suspended in 2-propanol were more stable than coal particles in CWSs.


*Keywords:* Coal–water slurry; Waste organic solvent; Coal–2-propanol slurry; Rheology

## 1. Introduction

Organic solvents have been widely used in various industries and waste solvent generation occurs during these applications. In Taiwan, waste organic solvents are categorized as hazardous wastes which must be collected by licensed collectors and disposed of at licensed facilities. According to Taiwan EPAs investigation [1], about 150,000 tonnes of waste organic solvents were produced annually in Taiwan. Considering the total capacity of all licensed collectors and disposal facilities of waste organic solvent in Taiwan, it can surely be assumed that some waste organic solvent have been disposed of improperly. Incidents of illegal dumping of waste organic solvents resulted in the pollution of surface water, soil, groundwater or marine water have been occurred constantly in recent years. Thus, efficient and environmentally sound management strategies to handle waste organic solvents in Taiwan are desperately needed. Distillation is a widely used process for the recovery of waste organic solvents [2,3]. Although effective, it is a relatively costly operation. A common alternative to distillation is incineration [4] but it also has some technical and environmental problems to burn waste organic solvents.

The use of coal–water slurry (CWS) as a fuel is regarded as a technology by which favorable economics and short-term commercialization could be realized, in comparison with the gasification or liquefaction technologies of coal [5]. CWS can be stored without the danger of coal-dust explosion, transported in pipelines and combusted like fuel oil in an environmentally benign manner [5]. The ideal of utilizing highly loaded CWS as a substitute fuel for oil has received worldwide attention since the late 1970s, and numerous studies have been made of its rheological properties in an effort to obtain acceptable fluidity while maintaining sufficient stability against sedimentation of the coal particles [6–8].

Considering the high heating value and the good compatibility with coal particles of organic solvents, it is interesting to explore the feasibility of using waste organic solvents as substitutes for water to prepare coal slurries. Compare to CWS, little information is available on the rheological properties of coal–organic solvent slurries. In this study, 2-propanol, an organic solvent widely used as a cleaning agent in the electronic industry [4], was used as a model organic solvent to prepare coal slurries. The rheological properties of coal–2-propanol slurries were examined and compared with that of CWS.

## 2. Experimental

### 2.1. Materials

The coal used in this investigation was a bituminous coal from China, and was provided by the Tai-power company. A typical

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Table 1
Proximate analysis of coal

| | % |
|---|---|
| Moisture | 7.3 |
| Volatiles | 27.0 |
| Fixed carbon | 57.2 |
| Ash | 8.5 |
| Heating value (kcal/kg) | 6630 |

analysis of this coal sample is shown in Table 1. The coal was used as received without any modification of its chemical and surface properties. Reagent grad 2-propanol ($CH_3CHOHCH_3$) obtained from Aldrich Chemical Co. were used. Distilled water was used in the preparation of CWS.

### 2.2. Coal slurries preparation

The raw coal was first crushed to a top size of 10 mm using a jaw crusher followed by dry grinding in a ball mill. The coal particles passing through 50 mesh, that is under 300 μm, was taken and used to prepare coal slurries. The particle size distribution of this coal sample was measured by the sieving method and laser diffraction method separately and is shown in Fig. 1.

Coal slurries with solid concentrations ranging from 10 to 40 vol.% were prepared by adding desired quantity of crushed coal into 500-ml plastic jar together with required volume of distilled water and/or 2-propanol. The jar was then ball milled with 400 g of l0-mm $Al_2O_3$ balls at 80 rpm for 1 h. This mixing condition resulted in homogeneous coal slurries without changing the particle size of coal particles.

### 2.3. Property measurements

The rheological properties of the coal slurries were measured using a Brookfield DV-III rheometer (cone-plate system). The stability characteristic of coal slurries was determined by settling test in a 100-ml graduated cylinder. After mixed manually end over end, the descending rate of supernatant/suspension interface and final sediment volume were determined.

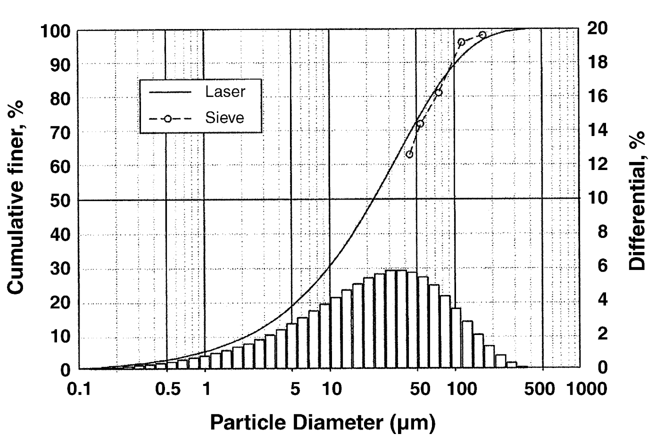


Fig. 1. Particle size distributions of coal.

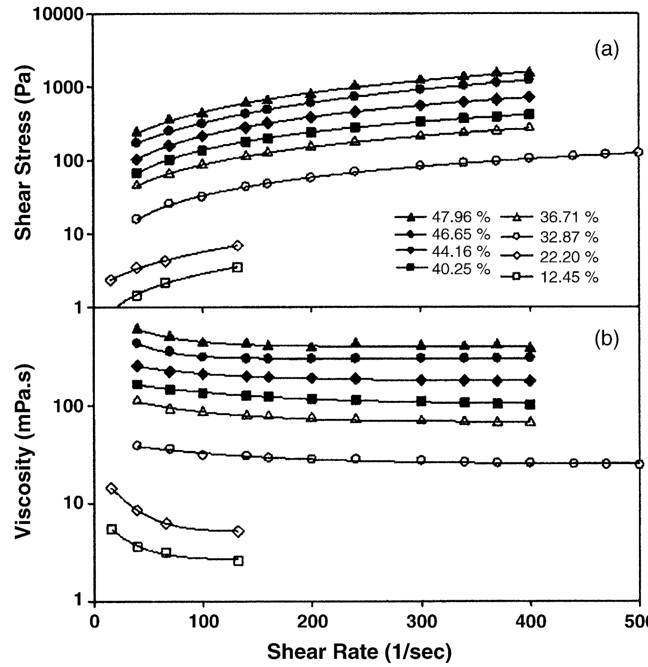


Fig. 2. Effect of solid concentration on rheological characteristics of coal–water slurries.

## 3. Results and discussion

### 3.1. Coal–water slurry versus coal–2-propanol slurry

The measured rheological properties of coal–water slurries and coal–2-propanol slurries were shown in Figs. 2 and 3, respectively, in the form of shear stress and viscosity versus shear rate plots. The solid concentrations of these slurries

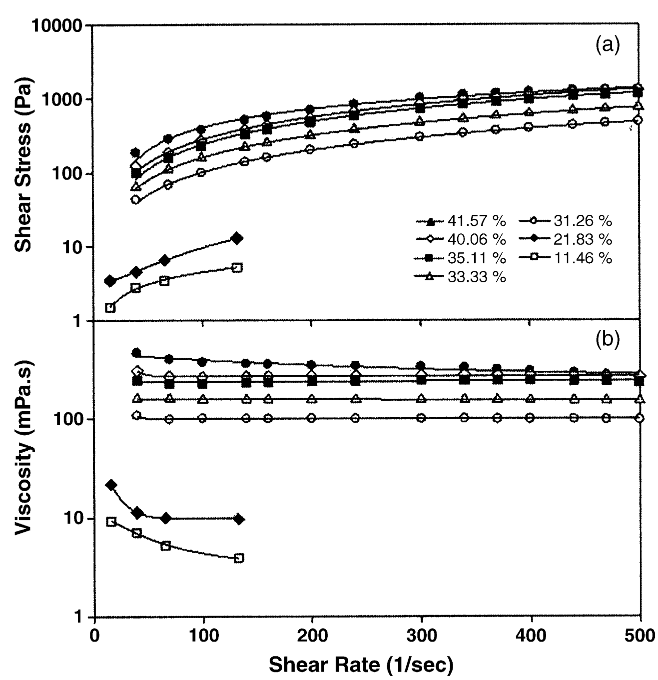


Fig. 3. Effect of solid concentration on rheological characteristics of coal–2-propanol slurries.

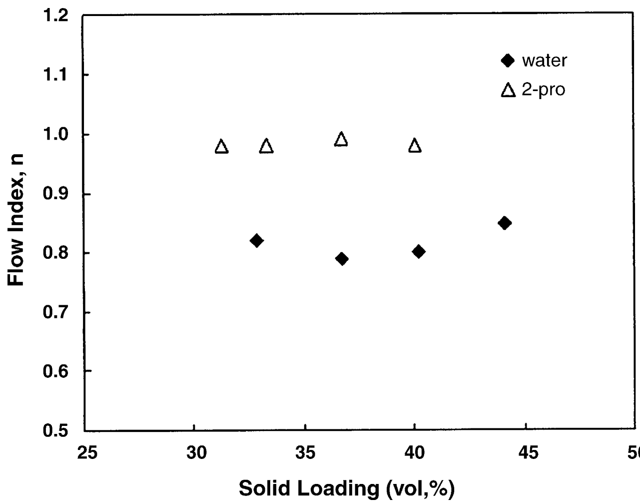


Fig. 4. Flow index values ($n$) for various coal slurries.

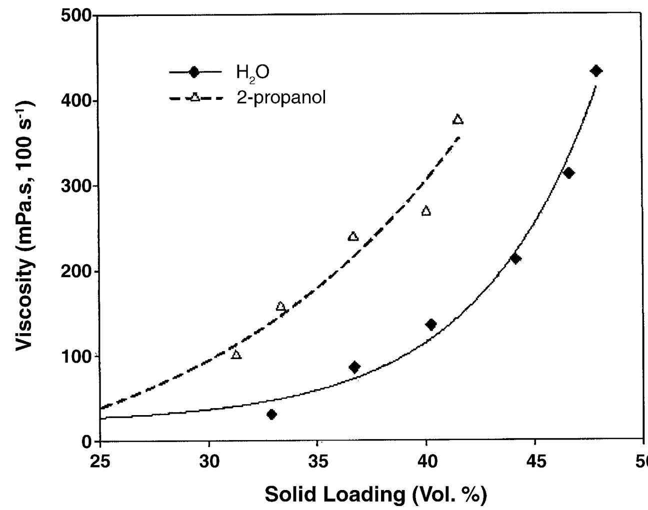


Fig. 5. Viscosity of coal slurries as a function of solid loading.

range from 10 to 40 vol.%. Over 40 vol.% solid, the slurries appeared as a highly viscous gel and this solid loading was found to be the practical limit of the measuring capability of the rheometer employed. Figs. 2 and 3 indicated that both CWS and coal–2-propanol slurries exhibited pseudo-plastic or shear-thinning behaviour with an apparent viscosity decreasing with increasing rate of shear. At solid loading higher than about 30 vol.%, the slurries exhibit viscoplastic behaviour with the presence of a yield stress, which is the minimum shear stress required to initiate flow. This kind of flow behaviour observed is typical with suspensions of micron-sized particles in which colloidal inter-particle forces are predominant in controlling the suspension rheology. As the distance between the particles is smaller with increasing concentration, inter-particle interactions become significant leading to formation of flocculated structure, which are broken subsequently down by shear resulting in shear-thinning and yield stress characteristics. The data from Figs. 2 and 3 are fitted to the power law:

$$\tau = K\gamma^n$$

where $K$ and $n$ are rheological constants, referred to as fluid consistency coefficient and flow behaviour index, respectively. For $n = 1$, this equation reduces to Newton's law of viscosity; hence, the departure of $n$ from unity indicates the degree of deviation from Newtonian behaviour. The values of $n$ for CWSs and coal–2-propanol slurries were determined and shown in Fig. 4. Clearly, coal–2-propanol slurries with values of $n$ close to 1 demonstrated a fluid behaviour approximate to Newtonian fluid. The hydrophobic coal surface was easily wetted by organic solvent such as 2-propanol. This good compatibility between coal particles and 2-propanol resulted in stable particle suspension in slurry which usually exhibit Newtonian behaviour. In addition, it was found from Figs. 2 and 3 that coal–2-propanol slurries shown higher viscosities comparing to CWS. The effect of solvent type and solid loading of coal slurries on viscosity is demonstrated more explicitly in Fig. 5 where the apparent viscosity (defined as the ratio of shear stress to the shear rate) determined at 100 $s^{-1}$ shear rate, is plotted as a function of solid loading in slurry. The effect of solvent type on viscosity is clear. CWSs with viscosity values below 200 mPa s could be prepared at 42 vol.% solid but coal–2-propanol slurries with same viscosity could only be prepared at solid loading less than 35 vol.%. It has been recognized that coals have a macromolecular structure that permits swelling in appropriate solvents [9,10]. Thus, in coal–2-propanol slurries the coal particles may be swelled by 2-propanol and resulted in an effective increase of solid loading in terms of vol.%. In addition, due to partition into coal particles less 2-propanol is available in slurry to increase the separation between the coal particles, thereby increasing the viscosity of slurries.

Fig. 6 shows the sedimentation rate of CWSs and coal–2-propanol slurries as a function of solid loading. In general coal–2-propanol slurries demonstrated lower settling rates compared to CWSs presumably due to good compatibility between coal particles and 2-propanol resulted in stable particle suspension in slurry. However, at solid loading higher than 30 vol.%, the higher concentration of coal particles leads to the formation of weak gel structures in the bulk, retarding the sedimentation

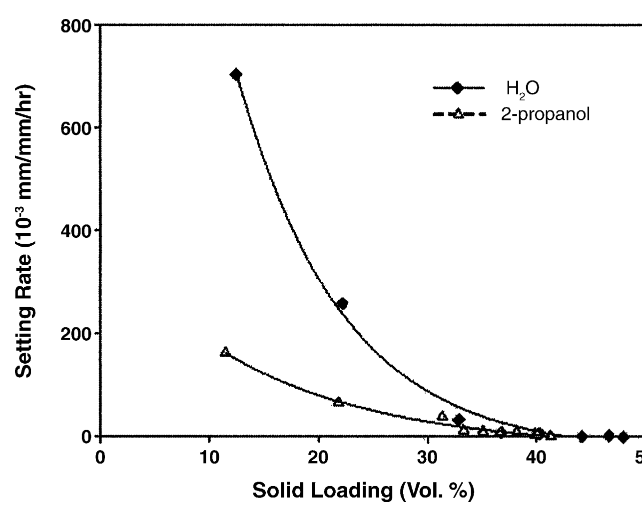


Fig. 6. Solid settling rate of coal slurries as a function of solid loading.

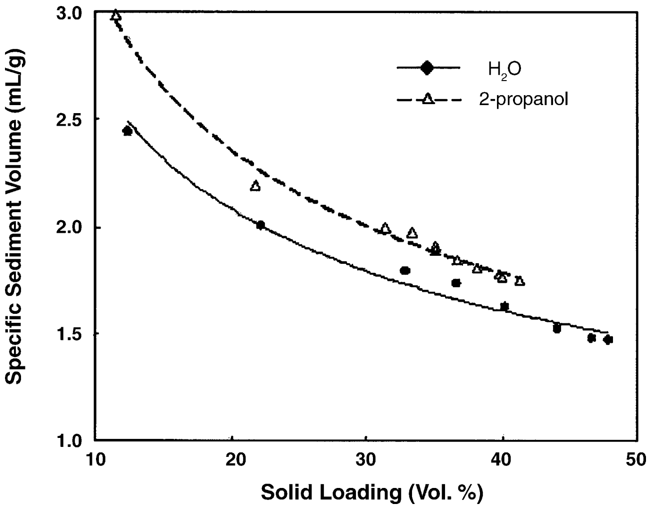


Fig. 7. Specific sediment volume of coal slurries as a function of solid loading.

of the particles in both slurries. Fig. 7 indicated the final sediment volumes of both slurries after settling as a function of solid loading. Coal particles in coal–2-propanol slurries always formed larger volume sediments compared to CWSs. In general, volume of sediment depends upon the stability of suspension. Stable particle suspensions pack efficiently to give dense sediments, whereas aggregated particles bridge readily and give loose sediments [11]. However, coal particles in coal–2-propanol slurries were swelled by 2-propanol and thus resulted in bulky sediment with loose structure even coal particles suspended in 2-propanol were more stable than coal particles in CWSs. In addition, the higher heating value of coal–water slurries (40 vol.%) and coal–2-propanol slurries (40 vol.%) was 10,500 and 14,750 Btu/lb, respectively, as determined by bomb calorimeter (ASTM D2015).

### 3.2. Water/2-propanol mixing effects

It is also interesting to probe the rheological properties of coal slurries prepared by solvents with different mixing ratio of water and 2-propanol. The effect of varying water/2-propanol composition on the viscosity of coal slurries are shown in Fig. 8. In the experiments, a constant solids loading of 35 vol.% was used. It is seen in Fig. 8 that coal slurries prepared with water/2-propanol mixtures were not ideal mixtures in terms of slurry viscosity and coal slurries shown a maximum viscosity at 4:6 mixing ratio of water/2-propanol. This viscosity maximum corresponded well to the viscosity maximum obtained for pure mixture (without coal particles) of water and 2-propanol (Fig. 9). The effect of varying water/2-propanol composition on the stability of coal slurries are shown in Fig. 10. In the experiments, a constant solids loading of 35 vol.% was used. It is observed that for coal/water/2-propanol system, the sediment volume increased with increasing 2-propanol content in slurries which indicated that sediment volume was pretty much controlled by the swelling of coal not by the stability of coal particles in suspension. In addition, coal slurries showed a minimum settling rate at 4:6 mixing ratio of water/2-propanol which also leaded to the highest slurry viscos-

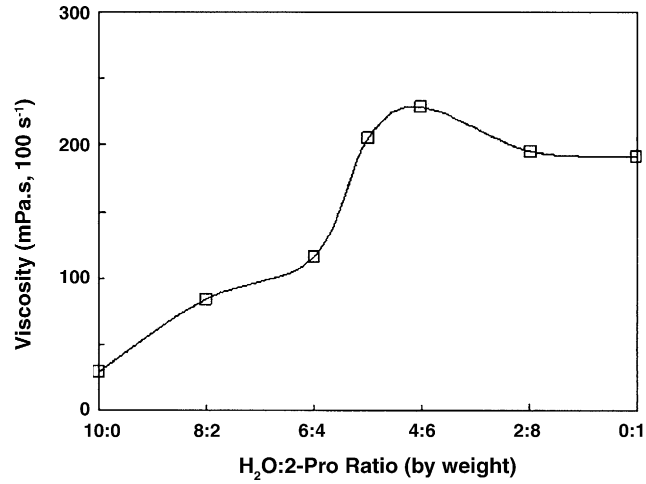


Fig. 8. The effect of varying water/2-propanol composition on the viscosity of coal slurries (35 vol.%).

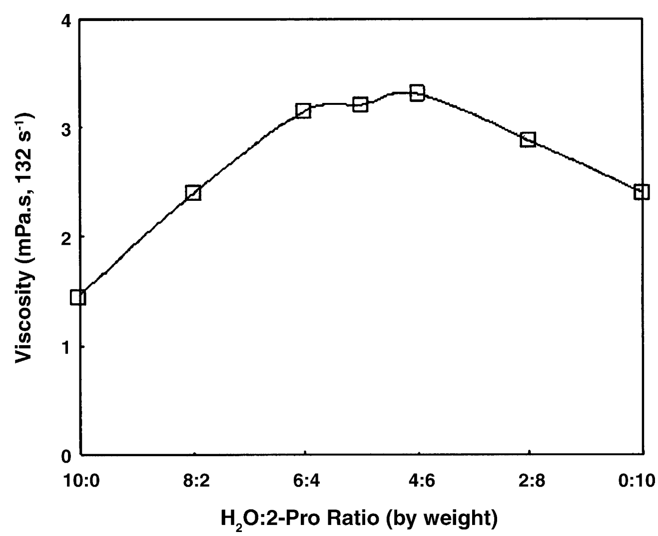


Fig. 9. The effect of varying water/2-propanol composition on the viscosity of pure mixture of water and 2-propanol.

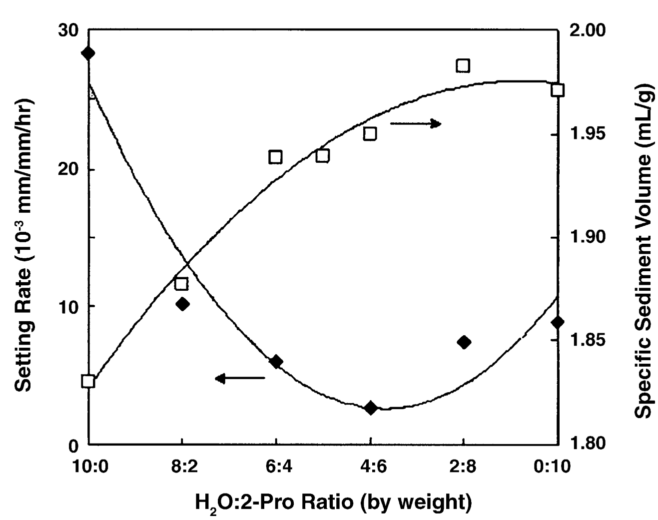


Fig. 10. The effect of varying water/2-propanol composition on the stability of coal slurries (35 vol.%).

ity according to Fig. 8. It is possible that the high viscosity of slurry hindered the settling of coal particles in this instance.

## 4. Conclusions

In this paper, the rheological properties of coal–2-propanol slurries were examined and compared with that of CWS. The good compatibility between coal particles and 2-propanol resulted in stable particle suspension in slurry which usually exhibit Newtonian behaviour. However, in coal–2-propanol slurries the coal particles may be swelled by 2-propanol which resulted in an effective increase of solid loading in terms of vol.% and less 2-propanol being available in slurry to increase the separation between the coal particles. Therefore, coal–2-propanol slurries usually shown higher viscosities comparing to CWSs at a fixed solid loading. In addition, coal–2-propanol slurries demonstrated lower settling rates (higher stability) compared to CWSs presumably due to good compatibility between coal particles and 2-propanol. However, coal particles in coal–2-propanol slurries were swelled by 2-propanol and thus resulted in bulky sediment with loose structure even coal particles suspended in 2-propanol were more stable than coal particles in CWSs. This no hard-pack sediments in coal–2-propanol slurries could easily be disintegrated by mild stirring even after long period of storage. This work may serve as a starting point for a more detailed study to optimize using waste organic solvents as substitutes for water to prepare coal slurries.

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