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# Effects of Stabilizing Agents on Stability and Rheological Characteristics of the Highly-Loaded Coal-Water Slurry

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***Abstract*—The effects of stabilizing agents on the rheological characteristics and static stability of highly-loaded coal-water slurry (HLCWS) were investigated in this study. Experiments were done on HLCWS prepared from sub-bituminous coal samples originated from Indonesia. Napthalene Sulfonate Formaldehyde (NSF) was the selected anionic dispersant used at fixed concentration. Three different stabilizers were chosen to study with a variation in quantity used. The results showed that the apparent viscosity of HLCWS increased due to the addition of stabilizer, resulting in a decrease in fluidity. However, static stability of HLCWS was found to effectively increase with the use of the stabilizer. Guar gum provided the most suitable apparent viscosity and static stability for HLCWS with 65% coal loading when compared to the others. It is also observed that the slurries exhibited non-Newtonian fluid behavior and expressed as pseudo plastic fluid.**

***Index Terms*—Coal-water slurry (CWS), rheology, static stability.**

## I. Introduction

Highly-loaded coal-water slurry (HLCWS) is an alternative energy option which consists of 60-75% coal powder, 25-40% water and about 1% additives [1]. Properties of coal, particle size distribution, type and amount of chemical additives and method of preparation of the slurry are considered as the factors affecting the characteristic of HLCWS. The most important characteristic of HLCWS based on its practical uses is viscosity. It is reported that the standard set on the apparent viscosity of CWS, which reference from fuel oil, is 1000 – 1200 cP at 100 rpm (shear rate = 122.36 $s^{-1}$) [2]. Nevertheless, other characteristics such as the solid content and static stability are also in need for the production of a good quality HLCWS. To maximize the solid content in HLCWS is necessary in order to maintain the energy from unit mass of it. But then an increase of solid content in HLCWS can cause an increase in viscosity and decrease in fluidity of the slurry. Chemical additives; i.e. dispersing and stabilizing agents, are widely used in HLCWS production to maximize the solid content. Dispersing agent is a surfactant for suspension of coal particles in water and stabilizing agent is a surfactant to improve the stability of the suspension HLCWS. It is of importance that the chemical additives, must be carefully chosen such that they should provide suitable viscosity or rheological characteristics [3, 4], including the desired stability, concerning the transportation and storage [5].

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There are a number of researches regarding the effects of chemical additives on coal-water slurry (CWS) [1-7]. In addition, there are several kinds of chemical additives that are in much of attention recently. The use of appropriate dispersing and stabilizing agents for the selected raw materials is necessarily investigated since coal properties are found to typically vary depending on coal rank and origin.

In this paper, experiments have been carried out by using sub-bituminous coal samples originated from Indonesia and the selected anionic dispersant to prepare the HLCWS samples. Three different stabilizers were chosen to study. The effects of studied stabilizing agents on the rheological characteristics and static stability of the prepared HLCWS were investigated and discussed.

## II. Experimental

### A. Materials

HLCWS were prepared with the sub-bituminous coal samples originated from Indonesia. Table 1 shows the proximate and ultimate analyses of the coal samples according to ASTM D3172 and ASTM D3175 respectively.

TABLE I: Proximate & Ultimate Analysis of the Coal Sample

| Proximate analysis (dry basis) | |
|---|---|
| Moisture (% wt) | 10.50 |
| Ash content (% wt) | 5.59 |
| Volatile Matter (% wt) | 42.31 |
| Fixed carbon (% wt) | 41.60 |
| Gross calorific value (Kcal/kg) | 5,878 |
| **Ultimate analysis (dry basis)** | |
| Oxygen (% wt) | 23.08 |
| Carbon (% wt) | 68.18 |
| Hydrogen (% wt) | 5.24 |
| Sulfur (% wt) | 0.16 |
| Nitrogen (% wt) | 0.71 |

Coal samples were pulverized to a particle size below 250 $\mu m$ by using a laboratory ball mill and subsequently sieved into two size fractions: 180-250 μm and 75-90 μm, since the bimodal distribution was preferred for the study. Naphthalene Sulfonate Formaldehyde (NSF, Molecular weight $2\times10^4$) was an anionic dispersing agent used for all prepared HLCWSs. Three commercial stabilizing agents; i.e. Sodium Carboxy- methyl Cellulose (CMC-Na, Molecular weight $8\times10^4$), Guar Gum (Molecular weight $2.2\times10^5$) and Arabic Gum (Molecular weight $5\times10^5$), were chosen to study.

*B. Preparation of the Highly-Loaded CWS Samples*

HLCWSs used in this experiment were prepared by mixing the coal samples of the two different particle size ranges mentioned above with the coarse to fine ratio at 0.6:0.4. De-ionized water and chemical additives were added to the mixture of coal samples in desired amounts in order to obtain the HLCWSs with coal loadings at 62 and 65 %wt. The amounts of the stabilizing agents chosen for the study were varied between 0.01-0.1 %wt, while NFS was fixed at 0.5 %wt throughout the experiment. After the mixing, the slurries were continuously stirred for 25 min to ensure homogenization. The prepared HLCWS samples were then allowed to stand for 5 min before the apparent viscosity measurement. During preparation, the temperature was maintained at 25°C.

*C. Determination of APPARENT viscosity and Rheology of the HLCWS*

The apparent viscosities of the highly-loaded CWSs were measured by MV-2000 series II Cannon® Rotary Viscometer. The shear rates were varied from 10-100 rpm at 25-30 °C. The rheological behaviors of the HLCWSs were then examined and described according to the Ostwald-de-Waele equations [8] as follows:

$$\tau = K\gamma^{n} \quad (1)$$

$$\eta = K\gamma^{n-1} \quad (2)$$

where τ is shear stress (dyne/cm$^2$), η is apparent viscosity (*mPa.s*), K is the rheological constant, γ is shear rate (s$^{-1}$) and n is the flow behavior index.

*D. Static Stability Test*

HLCWS samples were filled in a glass settling column with 35 mm diameter and 300 mm height. The initial height of the HLCWS bed was kept at 160 mm. After that, the height of interface was recorded every 1 hour until a constant height is reached. The height of interface was then plotted against time.[9]

## III. Result and Discussion

*A. Effect of Stabilizing Agent on the Apparent Viscosity of HLCWS*

The apparent viscosities of HLCWS samples obtained by employing solid loadings of 62% and 65% in the presence of different types and concentrations of stabilizing agents are given in Figure 1 and 2, respectively. As seen in the figures, it is observed that, for all slurries, the apparent viscosity increased when increasing the concentration of stabilizing agent regardless of the type. This is due to the fact that the stabilizing agents chosen for the study are hydrocolloids, in which the hydrophilic polymer has ability to absorb water and results in the decrease of free water in HLCWS when the stabilizing agents were added in. From fig. 1, it can be seen that only Arabic gum exhibited a linear relationship with the lowest in apparent viscosity value at the highest concentration used in this study when compared with the other two stabilizing agents. However, the 65% solid-loading slurries with the use of Arabic gum showed a non-fluidic characteristic and therefore their apparent viscosities could not be measured. From the apparent viscosity of HLCWS shown in both Fig. 1 and 2, Guar gum demonstrated the lowest apparent viscosity at the concentration at 0.03 %wt and also provided the lower apparent viscosity than that of CMC-Na at all concentration tested. This is because of the difference in the polymer structure; that is, CMC-Na is a polymer with complex polymeric long-chain aliphatic structure that would give high viscosity when dissolved in water, while Guar gum structure is linear with side chain polymer that would give low viscosity when compared with complex polymer. It can also be noticed from the figures that, when the stabilizers are below 0.05 %wt, all stabilizing agents displayed the apparent viscosity in the values below 1200 cP at shear rate applied of 100 rpm for the HLCWS with 62% loading, whereas both Guar gum and CMC-Na also gave the apparent viscosities below 1200 cP at shear rate applied of 100 rpm for the HLCWS with 65% loading.

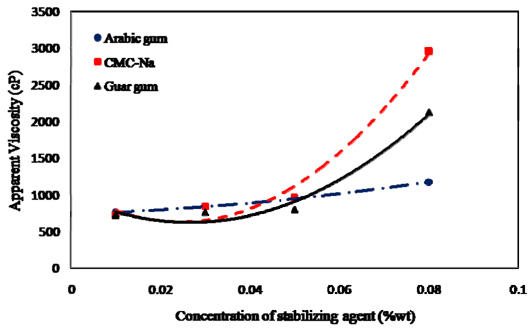


Fig. 1. Effect of stabilizing agent on the apparent viscosity of HLCWS with 62% coal loading and NSF 0.5 %wt.

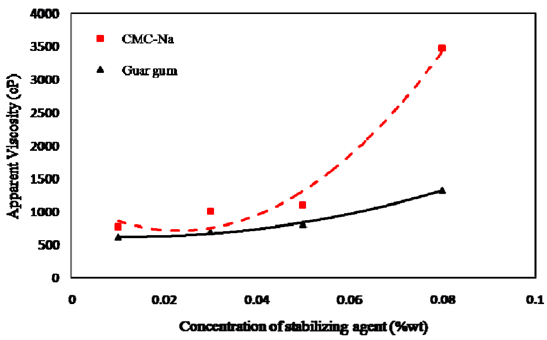


Fig. 2. Effect of stabilizing agent on the apparent viscosity of HLCWS with 65% coal loading and NSF 0.5 %wt.

From the correspondence between concentration of stabilizing agents and the apparent viscosity of CWS discussed above, it brings to consider explicitly on the variation of the apparent viscosity of HLCWSs with type of stabilizing agents and shear rate applied, as shown in Fig. 3 and 4. The HLCWSs with 62% and 65% coal loadings were prepared with the fixed concentrations of chemical additives; i.e. NSF 0.5 %wt and stabilizer 0.05 %wt. From the results shown in Fig. 3, it is observed that the apparent viscosities of HLCWSs by using CMC-Na and Guar gum as stabilizing agents were decreased when shear rate applied increased, resulting in an increase in fluidity. The same fashion can be seen in Fig. 4 when included Arabic gum as the stabilizer. This information is of interest when the rheological characteristics of the HLCWS have come into consideration.

It evidently implies the non-Newtonian fluid characteristics that can benefit the practical use.

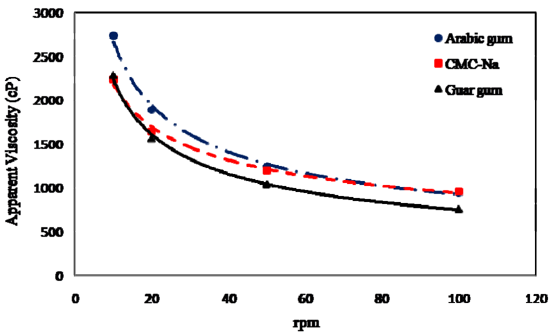


Fig. 3. Effect of stabilizer type and shear rate applied (rpm) on the apparent viscosity of HLCWS with 62% coal loading, NSF 0.5 %wt and stabilizer 0.05 %wt.

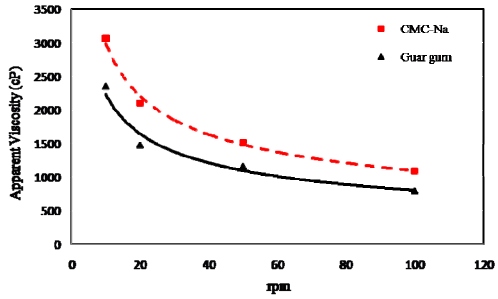


Fig. 4. Effect of type of stabilizer type and shear rate applied (rpm) on the apparent viscosity of HLCWS with 65% coal loading, NSF 0.5 %wt and stabilizer 0.05 %wt.

### B. Rheological Behavior of HLCWS

Fig. 5 shows the flow curves of HLCWSs prepared by using solid loadings 62% and 65% with NSF 0.5 %wt and stabilizers 0.05 %wt. It is obviously noticed from the figure that all curves exhibited non-Newtonian behavior, and the flow characteristics can be described by the power law model having the flow behavior index (n) less than 1, according to the Ostwald-de-Waele equations. As the results, it can be pointed out that all HLCWSs in the study showed the characteristics of non-Newtonian pseudo-plastic fluid. For the HLCWS prepared with 65% coal loading by using Guar gum 0.05 %wt as the stabilizing agent, the rheological model is given by $\tau = 6.7376\gamma^{0.559}$.The findings on rheological behaviors of the HLCWS prepared from the studied coal samples play crucial information for an analysis on the transport of HLCWS, the design of HLCWS pipelines, and the utilization of HLCWS.

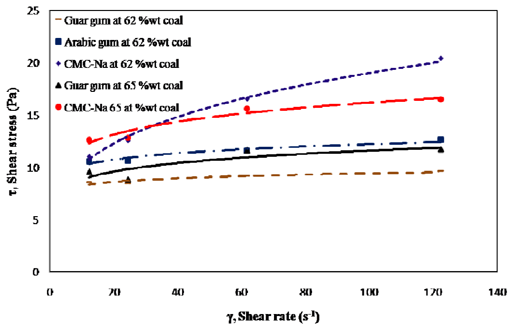


Fig. 5. the flow curves of HLCWSs prepared by using solid loadings 62% and 65 %, NSF 0.5 %wt and stabilizing agents 0.05 %wt.

### C. Static Stability of HLCWS

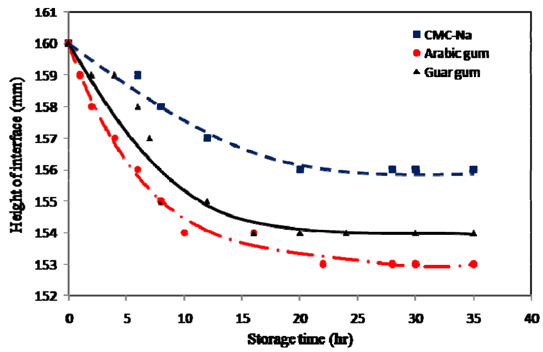


Fig. 6. Static stability of HLCWSs prepared with 62% solid loading by using NSF 0.5 %wt and stabilizing agents 0.05 %wt.

Fig. 6 shows the results on the static stability test for the HLCWSs prepared with solid loading 62%, NSF 0.5 %wt and the fixed concentration of different stabilizers at 0.05 %wt. In this figure, it can be seen that all HLCWSs tested displayed a rapid settling rate during the beginning of storage time (0 – 10 hr). A slower rate was then observed until the storage time reached approximately 20 hr that almost no sedimentation was observed. For the HLCWS that contained no stabilizer, the sedimentation was observed immediately with a very high settling rate and became at rest within 15 min. When compared among three stabilizers used, the HLCWS with the use of CMC-Na demonstrated the lowest settling rate. This can be explained by the difference in the structure of stabilizer. It is well known that CMC-Na has complex polymeric long-chain aliphatic structure and its carboxyl group causes hydrophilic property that the hydrophilic functional groups in the surface of coal can interact with and form a stable three-dimensional network structure, resulting in the declination in gravity sedimentation [2]. However, the three-dimensional network structures formed by CMC-Na can, in turn, prevent the coal particles from a free movement and therefore the higher in apparent viscosity can be expected. This fact can attribute to the limit in maximum coal loading for the prepared HLCWS. The non-fluidity of HLCWS with 65% loading by using CMC-Na was observed experimentally.

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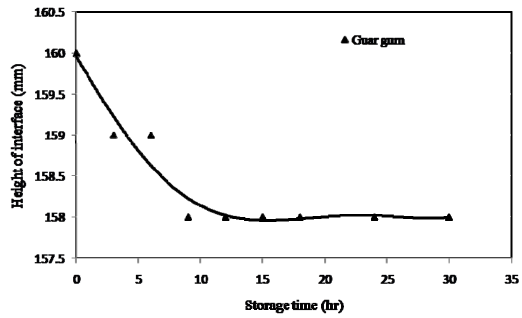


Fig. 7. Static stability of HLCWSs prepared with 65% solid loading by using NSF 0.5 %wt and Guar gum 0.05 %wt.

Fig. 7 illustrate the static stability test for the HLCWS prepared with solid loading 65% by using NSF at 0.5 %wt and Guar gum as stabilizer at 0.05 %wt. The same pattern as seen in Fig. 6 is observed in this figure, but the storage time that without sedimentation. It can be seen in Fig. 7 that the HLCWS without sedimentation occurred when the storage time reached approximately 12 hr. This is attributed to the fact that Guar gum structure is linear with side chain polymer that would not form three-dimensional network structure like CMC-Na. Nevertheless, it is worth to note that static stability of HLCWS has to be negotiated with its apparent viscosity in practical uses.

## IV. Conclusion

The effects of stabilizing agents on the rheological behaviors and static stability of highly-loaded coal-water slurry (HLCWS) have been observed. The anionic dispersing agent: NSF and three different stabilizers: CMC-Na, Guar gum and Arabic gum were used to prepare the studied HLCWSs from sub-bituminous coal samples originated from Indonesia. The results showed that the apparent viscosity of HLCWS increased due to the addition of stabilizer, resulting in a decrease in fluidity. However, the addition of suitable type and concentration of stabilizer can improve stability of HLCWS for its practical uses, especially in HLCWS storage and transportation. It is concluded from the results that Guar gum at 0.05 %wt is a suitable stabilizing agent used for the preparation of HLCWS. With this condition, the appearance of HLCWS sample is homogenous, good fluidity and acceptable in apparent viscosity and static stability.

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