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EXPERIMENTAL INVESTIGATION OF STATIC SETTLED CONCENTRATION OF MULTI-SIZED COKING COAL-WATER SLURRY

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In this experimental study, the effect of variation of coking coal concentration (C_w) and particle size proportions on static settled concentration by weight (C_{wss}) of multi-sized coking coal-water slurry is investigated using a graduated cylindrical flask. It is observed that, at 72 hours, the multi-sized coking coal-water slurry achieved maximum static settled concentration for each slurry concentration. From 0 hours to 24 hours, static settled concentration increases and then decreases from 24 hrs to 72 hours in each case of coking coal concentration and particle size proportion. For first particle size combination C_1 = [(4 mm to 3.15 mm) + (3.15 mm to 0.5 mm) + (less than 0.5 mm)], maximum C_{wss} at 72 hours decreases from Cw = 50% to 55% and then increases from 55% to 65% for both sets of particle size proportions P_{C11} and P_{C12}. For second particle size combination C_2 = [(6.7mm to 3.15mm) + (3.15 mm to 0.5 mm) + (less than 0.5 mm)], maximum C_{wss} at 72 hours increases from C_w = 50% to 65% for particle size proportions P_{C21} and for P_{C22}, maximum C_{wss} decreases from C_w = 50% to 55% and then increases from 55% to 65%. Out of the the selected concentrations of coking coal, the optimum value of Cw is observed as 55% for each set of particle size proportions P_{C11}, P_{C12}, P_{C21}, and P_{C22} corresponding in both particle size combinations C_1 and C_2.

KEYWORDS: Coking Coal, Slurry, Static settled concentration, Particle Size Proportion.

NOTATION

C_w	Concentration of coking coal sample (%)
C_{wss}	Static settled concentration by weight (%)
C_1	First particle size combination
C_2	Second particle size combination
m_s	Mass of solid particles in settled part of slurry (g)
P_{C11} and P_{C12}	Sets of particle size proportions corresponding to C_1
P_{C21}, and P_{C22}	Sets of particle size proportions corresponding to C_2
PSD	Particle size distribution
V_{lm}	Volume of water in settling slurry = $V_l - (V_{mi} - V_m)$ (ml)
V_{mi}	Initial volume of slurry (ml)
V_m	Volume of settled slurry at any given time (ml)
V_l	Volume of water taken (ml)
W_s	Total required weight of coking coal sample (g)

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W_w	Weight of 500 ml water taken in measuring cylinder (g)
ρ_l	Density of water (g/cm^3)

1. INTRODUCTION

Coal plays an essential role in the development of a country as it is one of the significant sources of energy. Coal available in its natural form is used for power generation while coking coal is used in metallurgical and steel making industries. Hence, it is transported to the vicinity of use in its natural form or as a refined product (National Academy of Engineering 1974). Transport of coking coal to the point of use in the form of slurry through pipelines and launders is one of the efficient means which is growing day by day (National Academy of Engineering 1974). For transporting the coal-water slurry, pipelines are used for long distances while open channel flumes/launders are used in the mining industries to transport slurries during processing and to disposal sites (Burger 2014).

For transporting the coal as slurry through pipeline and flumes, the coal is mixed with water and pumped through a pipe or channelized through the open channel flumes to the point of use where the coal is removed from the water by means of centrifuges, vacuum filters, or thermal drying (National Academy of Engineering 1974). Two-phase system of slurry and properties associated with coal (specific gravity, moisture content, ash content, hardness, size and shape of coal particles, surface texture and particle size distribution) makes its pumping more complex (Sheshadri et al. 1997; Kaushal et al. 2002). The concentration of coal in water, temperature and viscosity are the properties of coal water slurry (National Academy of Engineering 1974).

As water plays a significant role in the preparation of slurries, its usage and availability are critical in countries where there are strict water usage management programs. Therefore a particular slurry transportation system (pipeline or open channel flume) becomes unfeasible if its water requirement is very high. The optimization of pipeline and flume design involves the maximization of solids transport efficiency while at the same time, reduces water usage (Burger 2014). To utilize a lower amount of water for transporting the maximum amount of coal through pipelines and open channel flumes/launders, the concentration of coal has to be increased beyond 50% by weight (Faddick 1979). When there is a power cut for long durations than possibilities of pipeline choking increases due to the settlement of coarser coal particles at the bottom of the pipe which increases the chances of pipeline burst due to abrasion of pipe material (National Academy of Engineering 1974). Mixing of powdered particles along with coarser particles will help in reducing the viscosity and provide ease in the movement of slurry at lower velocities (National Academy of Engineering 1974).

Nguyen et al. (1997) experimentally investigated the effect of variation of particle sizes on rheological behaviour of unimodal, bimodal and trimodal coal-water slurry. They concluded that at any given concentration of solid, the slurry viscosity can significantly be reduced by mixing two or more different size fractions of solid and by controlling the amount of the different size fractions. An experimental study conducted by Mishra (1996) for the flow of multi-sized slurry in horizontal pipelines reveals that static settled concentration increases with increase in particle size and decreases with an increase in particle density. Gandhi and Borse (2002) used sand-water slurry to analyze the effect of particle size distribution on the wear of cast iron pipe. They observed a linear increase in wear with an increase in particle size. On the basis of specific energy consumption, optimum concentration of solid is generally 5-10% lower than the maximum static settled concentration (Biswas et al. 2000; Singh et al. 2017).

Number of studies has been conducted on the effect of particle size distribution on the rheology of the coal-water slurry (Leong et al. 1987; Round and Hessari 1987; Toda and Kuriyami 1988; Sengun and Probstein 1989; Turian et al. 1992; Roh et al. 1995; Singh et al. 2016). No study has been carried out to find the maximum settled concentration value at higher concentrations of multi-sized coking coal-water slurry for its transportation through the pipeline and launder.

In this paper, an effort has been made to experimentally investigate the behavior of maximum static settled concentration under the variation of particle size proportion and concentration for highly concentrated multi-sized coking coal-water slurry.

2. MATERIALS AND METHODOLOGY

The sieve analysis method was used to obtain the PSD of coking coal particles larger than 75 μm and for the PSD of coking coal particles smaller than 75μm, hydrometer analysis technique was used. IS:460 standard sieves with sieve arrangement of 9.5 mm, 6.7 mm, 3.15 mm, 2.36mm, 1.18 mm, 710 μm, 500μm, 300 μm, 150 μm and 75 μm was used for sieve analysis. In sieve analysis, 1000 g of oven dried coking coal sample was sieved through sets of sieves and cumulative percent of solid retained on the sieves and cumulative percent of solid passed through the sieves was calculated using standard procedures. The standard 151H hydrometer was used for hydrometer analysis of particle sizes less than 75 μm. The final PSD of coking coal was plotted on semi-log graph, which is presented in Figure 1.

For studying the effect of C_w and particle size proportions on C_{wss} of multi-sized coking coal-water slurry, the oven-dried coking coal was sieved by mechanical shaker through the first sieve arrangement of 4 mm, 3.15 mm, 0.5 mm and pan and second sieve arrangement of 6.7 mm, 3.15 mm, 0.5 mm and pan to obtain the required/selected particle size ranges 4 - 3.15 mm, 6.7 - 3.15 mm, 3.15 - 0.5 mm and less than 0.5 mm. To prepare the coking coal-water slurry having multi-sized distribution, two combinations (C_1 and C_2) of particle sizes was considered from the selected particle size ranges (table 1). For the variation of particle size proportion in the particle size combinations C_1 and C_2, two sets of particle size proportions P_{C11} and P_{C12} were considered for particle size combination C_1 and two sets of P_{C21} and P_{C22} for particle size combination C_2 (Table 1).

500 ml tap water were taken in 1200 ml cylindrical measuring flask having a diameter of 50 mm and this amount of water in the flask was weighed. Now according to required slurry concentration (C_w = 50%, 55%, 60% and 65% by weight), the amount of total coal required were calculated and the weight of the proportions of different particle size ranges in the total amount of required coking coal were also calculated. This weighted coking coal sample was then poured in measuring cylinder containing 500 ml tap water and the mixture was well shaken till it got mixed completely and uniformly. After thorough mixing, the cylinder was placed on the undisturbed surface. The reading of free water surface level and settled slurry level was recorded at 0, 24, 28, 48, 72 and 96 hrs. and then C_{wss} was calculated. These steps were repeated for C_w = 50% to 65% in both cases of C_1 and C_2.

The equations used for calculating the required weight of coking coal sample (W_s) and static settled concentration by weight (C_{wss}) of coking coal are given below:

$$C_w = \frac{W_s}{W_s + W_w} \tag{1}$$

$$C_{w_{ss}} = \frac{m_s}{(\rho_l V_{lm} + m_s)} \tag{2}$$

Table 1

Selected particle size combinations and proportions of particle size ranges

C_w(%)	**Particle size combination C_1 = [(4 mm to 3.15 mm) + (3.15 mm to 0.5 mm) + (less than 0.5 mm)]**			
50, 55, 60, 65	Proportions of particle size range in P_{C11}	$P_{4mm\ to\ 3.15mm}$ = 10%	$P_{3.15mm\ to\ 0.5mm}$ = 45%	$P_{less\ than\ 0.5mm}$ = 45%
	Proportions of particle size range in P_{C12}	$P_{4mm\ to\ 3.15mm}$ = 15%	$P_{3.15mm\ to\ 0.5mm}$ = 42.5%	$P_{less\ than\ 0.5mm}$ = 42.5%
where P_{C11} = [($P_{4mm\ to\ 3.15mm}$ = 10%) + ($P_{3.15mm\ to\ 0.5mm}$ = 45%) + ($P_{less\ than\ 0.5mm}$ = 45%)] P_{C12} = [($P_{4mm\ to\ 3.15mm}$ = 15%) + ($P_{3.15mm\ to\ 0.5mm}$ = 42.5%) + ($P_{less\ than\ 0.5mm}$ = 42.5%)]				
Cw(%)	**Particle size combination C_2 = [(6.7 mm to 3.15 mm) + (3.15 mm to 0.5 mm) + (less than 0.5 mm)]**			
50, 55, 60, 65	Proportions of particle size range in P_{C21}	$P_{6.7mm\ to\ 3.15mm}$ = 10%	$P_{3.15mm\ to\ 0.5mm}$ = 45%	$P_{less\ than\ 0.5mm}$=45%
	Proportions of particle size range in P_{C22}	$P_{6.7mm\ to\ 3.15mm}$ = 15%	$P_{3.15mm\ to\ 0.5mm}$ = 42.5%	$P_{less\ than\ 0.5mm}$ = 42.5%
where, P_{C21} = [($P_{6.7mm\ to\ 3.15mm}$ = 10%) + ($P_{3.15mm\ to\ 0.5mm}$ = 45%) + ($P_{less\ than\ 0.5mm}$ = 45%) P_{C22} = [($P_{6.7mm\ to\ 3.15mm}$ = 15%) + ($P_{3.15mm\ to\ 0.5mm}$ = 42.5%) + ($P_{less\ than\ 0.5mm}$ = 42.5%)]				

3. RESULTS AND DISCUSSION

From PSD, the maximum particle size of coking coal was recorded as 9500 µm. The median diameter, d_{50}, of coking coal particle is 600 µm (=0.6 mm) and d_{90}, d_{85}, d_{25} and d_5 are 7000 µm, 3700 µm, 190 µm and 59 µm respectively. Only 8.423% particles are finer than 75 µm, 89.53% particles are finer than 6700 µm, nearly 86% particles are finer than 4000µm, 83.59% particles are finer than 3150 µm and 45.42% particles are finer than 500 µm. 2.41%, 5.9%, and 38.2% particles lie in the range of 4000-3150 µm, 6700-3150 µm and 3150-500 µm respectively.

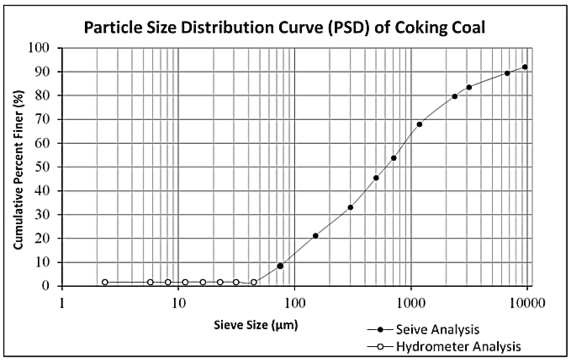


Figure 1. Particle size distribution of coking coal sample

From the experimental study, it is observed that the multi-sized coking coal-water slurry achieved maximum static settled concentration at 72 hours (readings were taken at 96 hour for surety) for each coking coal concentration (C_w) and particle size combinations C_1 and C_2.

Table 2

Variation of C_{wss} with time and C_w for particle size proportion sets P_{C11} and P_{C12} in particle size combination C_1

C_W (%)	Time (hrs)	$P_{C11} = (P_{4mm\ to\ 3.15mm} = 10\%) + (P_{3.15mm\ to\ 0.5mm} = 45\%) + (P_{less\ than\ 0.5mm} = 45\%)$	$P_{C12} = (P_{4mm\ to\ 3.15mm} = 15\%) + (P_{3.15mm\ to\ 0.5mm} = 42.5\%) + (P_{less\ than\ 0.5mm} = 42.5\%)$
		C_{wss} for P_{C11}	C_{wss} for P_{C12}
50	0	49.86%	49.74%
	24	66.99%	64.96%
	28	66.81%	64.87%
	48	65.41%	63.95%
	72	64.73%	63.21%
	96	64.73%	63.21%
55	0	54.87%	55%
	24	63.26%	63.4%
	28	62.74%	63%
	48	62.29%	62.61%
	72	62.1%	62.55%
	96	62.1%	62.55%
60	0	59.87%	59.75%
	24	64.7%	64.87%
	28	64.64%	64.76%
	48	64.56%	64.42%
	72	64.23%	64.25%
	96	64.23%	64.25%
65	0	64.88%	64.74%
	24	69.67%	69.39%
	28	69.57%	69.35%
	48	68.99%	68.87%
	72	68.49%	68.51%
	96	68.49%	68.51%

From Tables 2 and 3, it can be noted that, for both cases of particle size combinations C_1 and C_2, static settled concentration increases from 0 hour to 24 hour and then decreases from 24 hour to 72 hour in each case of coking coal concentration (C_w) and particle size proportion sets P_{C11}, P_{C12}, P_{C21} and P_{C22}.

Table 3

Variation of C_{wss} with time and C_w for particle size proportion sets P_{C21} and P_{C22} in particle size combination C_2

C_W (%)	Time (hrs)	$P_{C21} = (P_{6.7mm\ to\ 3.15mm} = 10\%) + (P_{3.15mm\ to\ 0.5mm} = 45\%) + (P_{less\ than\ 0.5mm} = 45\%)$	$P_{C22} = (P_{6.7mm\ to\ 3.15mm} = 15\%) + (P_{3.15mm\ to\ 0.5mm} = 42.5\%) + (P_{less\ than\ 0.5mm} = 42.5\%)$
		C_{wss} for P_{C21}	C_{wss} for P_{C22}
50	0	49.79%	49.79%
	24	63.02%	66.22%
	28	62.98%	66.12%
	48	62.47%	65.61%
	72	62.08%	64.84%
	96	62.08%	64.84%
55	0	54.8%	54.8%
	24	63.19%	63.27%
	28	62.64%	62.87%
	48	63.73%	63.79%
	72	63.33%	63.33%
	96	63.33%	63.33%
60	0	59.81%	59.81%
	24	64.81%	65.15%
	28	64.75%	65.09%
	48	64.7%	64.92%
	72	64.3%	64.36%
	96	64.3%	64.36%
65	0	64.82%	64.82%
	24	68.79%	68.53%
	28	68.63%	68.53%
	48	68.38%	68.23%
	72	67.87%	67.72%
	96	67.87%	67.72%

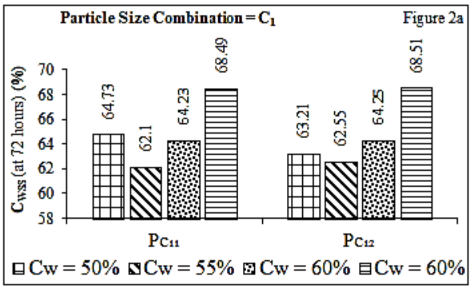
From Figures 2a and 2b, it can be noted that, for particle size combination C_1, maximum static settled concentration (C_{wss}) at 72 hours decreases from C_w = 50% to 55% and then increases from 55% to 65% for both sets of particle size proportions P_{C11} and P_{C12}. For second particle size combination C_2, maximum static settled concentration (C_{wss}) at 72 hours increases from C_w = 50% to 65% for particle size proportions P_{C21} and for P_{C22}, maximum static settled concentration (C_{wss}) decreases from C_w = 50% to 55% and then increases from 55% to 65%.

From Figures 2a and 2b, it is observed that, in case of particle size combination C_1 (Figure 2a), with increase in the proportion of coarser particles from particle size proportion set P_{C11} to P_{C12}, the C_{wss} decreases for C_w = 50% and increases for C_w = 55%, 60% and 65%. While in case of particle size combination C_2 (Figure 2b), with increase in the proportion of coarser particles from particle size proportion set P_{C21} to P_{C22}, C_{wss} increases for C_w = 50% and 60%, decreases for C_w = 65% and remain same for C_w = 55%.

From Figure 2a and 2b, it is observed that, in case of particle size combination C_1 (Figure 3a), with increase in the proportion of coarser particles from particle size proportion set P_{C11} to P_{C12}, the C_{wss} decreases for C_w = 50% and increases for C_w = 55%, 60% and 65%. While in case of particle size combination C_2 (Figure 3b), with increase in the proportion of coarser particles from particle size proportion set P_{C21} to P_{C22}, C_{wss} increases for C_w = 50% and 60%, decreases for C_w = 65% and remain same for C_w = 55%.

From Figures 2a and 2b, it is observed that when coarser particle size increases from 4 mm in particle size combination C_1 to 6.7 mm in particle size combination C_2, the C_{wss} increases for C_w = 55% and 60% and decreases for C_w = 50% and 65% in particle size proportion sets P_{C11} and P_{C21} while C_{WSS} increases for C_w = 50%, 55% and 60% and decreases for C_w = 65% in particle size proportion sets P_{C12} and P_{C22}.

In both case of particle size combinations C_1 and C_2 and their corresponding particle size proportion sets P_{C11}, P_{C12}, P_{C21} and P_{C22}, the optimum concentration of coking coal-water slurry was found as 55% by weight, as the difference between maximum static settled concentration (C_{wss}) at 72 hours and the slurry concentration (C_w) was within the range of 5% - 10%.



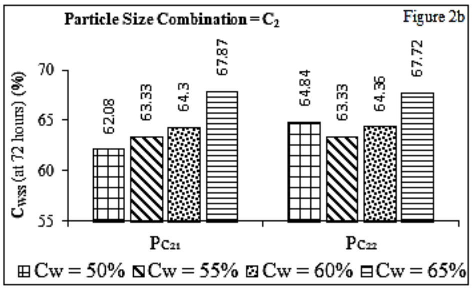


Figure 2. (2a and 2b) Variation of C_{wss} with particle size range proportions P_{C11} and P_{C12} at 72 hours for C_w = 50%, 55%, 60% and 65% by weight in particle size combination C_1 and C_2

4. CONCLUSIONS

From the present study, it is concluded that maximum static settled concentration of coking coal-water slurry at 72 hours increases with increase in coking coal concentration and proportions of particle size ranges in both cases of particle size combinations C_1 and C_2 but this trend is not same for every case of particle size proportion in both particle size combinations C_1 and C_2. Out of the selected coking coal concentrations, C_w = 55% is the optimum concentration of coking coal-water slurry in both particle size combinations C_1 and C_2 and their corresponding particle size proportion sets P_{C11}, P_{C12}, P_{C21} and P_{C22}. This study can further be extended for developing a method to optimize the coking coal-water slurries with maximum amount of solid in minimum amount of water and with minimum viscosity for its transportation through pipeline and launder.

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