

Experimental Evaluation of Cohesion Properties for Various Coals

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Abstract

Assessing the handling properties of coal becomes a major issue for the operation of a fuel supply system in power plants, due to the increased types of coal imported into Korea. In this study, the cohesion strengths of 13 bituminous and sub-bituminous coals from different countries were tested by measuring the amount of force that leads to a failure of consolidated particles. The particle size was in the range of 0.1-2.8 mm, which represents the coarse particles before pulverization. While the cohesion strength was proportional to the compression force in the tested range, the effects of the surface moisture content and the weight fraction of fines were crucial for cohesive coals. At fixed conditions of surface moisture and particle size, large variations were found in the cohesion propensity between coals. For coals of 0.1-0.5 mm with the moisture added close to the critical value, cohesive coals had the density over 900 kg/m³ after consolidation. The cohesion propensity was not correlated with the basic properties of coals with sufficient statistical significance.

Keywords : Coal, cohesion, compression, handleability, moisture content

I. INTRODUCTION

Despite the concern on greenhouse gas emission, coal is the dominant source of power generation in the world, responsible for 40.6% in 2010 [1]. The use of coal is also important in South Korea, as it generates 39.9% of electricity in 2010 [2]. Hard coals or high rank coals have been the main fuel for power generation in South Korea. However, due to the decreasing reserve and increasing mining costs, the use of low rank coals has recently increased [3]. South Korea imports 97% of its coal [2] from various countries including Australia, Indonesia, and Russia. More than 48 types of coals were imported in 2010 by Korea South East Power alone, one of five major power supply companies. Due to the large variation between coals, promptly analyzing detailed fuel properties has become crucial for the stable operation of power plants. In terms of the boiler, important fuel properties include the combustion and ash slugging/fouling characteristics of individual coals and their blends [3][4]. For the handling and pre-processing of coals, self-heating propensity and cohesion properties are crucial [5][6].

Evaluating the handling properties of coals can minimize the cohesion and blockage problems incurred during the processes from storage to size reduction [5]. Coal stored in yards is wet since coal stockpiles are exposed to the weather and are often sprayed with water to prevent spontaneous combustion. In processing coal for size reduction and combustion, the accumulation and subsequent cohesion of wet particles cause blockages in equipment such as hoppers, chutes, bunkers, and conveying systems. The cohesion problems are not severe after the coal is ground to fine particles in a pulverizer, since it is dried and transported by preheated primary air.

Coal particles coagulate when they are accumulated and compacted by gravity or by other mechanical forces during handling processes. The basic mechanism for adhesion of fine particles is the van der Waals force [7]. Since it is inversely

proportional to the square of the distance between particles, however, the force is not sufficiently high for dry particles with a particle size of about 1 mm or larger. When free moisture is present between voids of particles, it forms pendular bridges with a stronger bonding strength between particles by surface tension and capillary force [7]. Therefore, the key parameters for the handling properties of coal are moisture content and particle sizes. With increasing the moisture content, the cohesion propensity increases rapidly to a peak [8]-[11]. Above the peak point, extra water between particles loosens the bond and the cohesion gradually weakens. Particle sizes determine the contact area between particles and, therefore, larger proportions of fines increase the cohesion propensity. Mikka and Smitham [8] found that coals at a high level of fines become more sensitive to moisture content. The ash content [12][13] and the types of clay minerals [8] also influence the cohesion properties.

In the research reported in the literature, various test methods have been used for measuring the handleability of solid particles [5][8]. Common methods include the Jenike shear cell, Durham cone test, Johanson hang-up indicizer, and the Edinburgh cohesion test. The Jenike shear cell method measures the shear force required to move the top half of a horizontal cylinder in which particles are filled and consolidated. This method is standardized (ASTM D6128) for the design of bins and chutes for general solids. The Durham cone test assesses the discharge time (flow time) of coal particles from a vibrating hopper. The Johanson hang-up indicizer method compresses coal particles in a cylindrical mound for a set period of time and measures the downward force required to fail the sample after part of the base is removed [14]. The Edinburgh cohesion test consolidates particles in a cylindrical mold of 100 mm in diameter and then measures the force leading to a collapse of the sample after the mold is removed [15]. The above-mentioned methods require a large volume of samples to obtain representative data for coals of various sizes. However, it is difficult to control test

Table 1. Summary of fuel properties of tested coals

Coal	Country of origin ¹⁾	Proximate analysis (wt.%ad)			Ultimate analysis (wt.%ad)			HHV (MJ/kg)	Key compounds in ash composition (wt.%)			
		IM	Ash	VM/FC	C	H	O		SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃
A	AU	1.20	15.97	0.61	68.90	3.91	5.76	28.25	75.78	18.78	0.20	1.72
B	AU	1.41	14.83	0.65	68.31	4.34	6.86	28.25	63.83	23.63	1.74	4.64
C	AU	1.30	18.28	0.55	65.47	3.92	7.34	26.67	67.57	25.1	0.35	2.02
D	IN	8.58	14.25	1.01	50.2	4.09	21.56	18.99	57.86	25.01	2.30	9.67
E	AU	1.26	20.53	0.51	64.09	3.94	6.46	26.51	65.16	22.35	0.71	6.11
F	US	9.34	12.44	0.92	57.69	3.16	15.53	21.98	58.07	19.11	1.81	15.99
G	RU	3.14	15.4	0.84	61.94	4.02	14.57	24.27	60.56	27.48	3.18	3.47
H	AU	4.39	10.27	0.70	68.79	5.06	9.31	28.9	50.08	23.25	10.99	6.61
I	IN	4.47	14.85	0.56	70.95	4.69	3.10	30.22	54.19	25.06	6.08	7.81
J	AU	1.41	16.12	0.68	62.50	3.94	14.37	24.24	48.76	25.65	11.44	7.77
K	IN	9.27	11.36	1.04	59.50	3.84	11.21	24.26	60.93	16.16	4.00	10.41

¹⁾IM: inherent moisture, VM: volatile matter, FC: fixed carbon, AU: Australia, IN: Indonesia, RU: Russia, US: United States

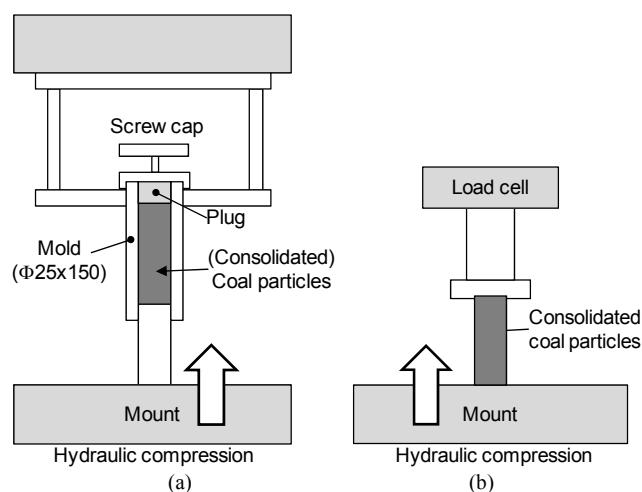


Fig. 1. Schematic of (a) the compression rig and (b) cohesion strength test.

parameters such as the moisture content and particle size distribution for various coals.

This study investigates the cohesion properties of 14 sub-bituminous and bituminous coals for coarse particles (0.1-2.8 mm) before pulverization. As an indicator for the cohesion strength, the force leading to a failure of consolidated particles was measured for the samples pre-conditioned with different moisture contents and particle sizes. Then, the interrelations of cohesion strength with the basic fuel properties were evaluated.

II. MATERIALS AND METHODS

A. Coal samples

The coal samples were collected from the yard at the Boryeong power plant (Korea Midland Power Co. Ltd.) for 9 types of coal in October 2012 and 4 types of coal in February 2013. All the coals sampled had been stored in the yard for less than 1 month. The samples were then crushed and stored in sealed bags after air-drying. The proximate analysis was carried out based on the standard methods (ASTM D3172). The ultimate analysis was conducted using an elemental analyzer (EA1108, Fisons Instrument) for C, H, N, and S. The higher heating value was estimated using the Dulong equation. The ash composition was analyzed using an ICP-OES (CAP 6300 Duo, Thermo Scientific Co.) and ICP-MS (7700x, Agilent Technologies) for

key elements and converted to the respective oxide composition.

Table 1 lists the summary of the fuel properties of 13 coals tested. The coals consisted of sub-bituminous and bituminous with a various range of properties. The inherent moisture content was between 1.20% (coal A) and 10.09% (coal M). The ratio of volatile matter and fixed carbon (VM/FC) ranged from 0.51 (coal E) to 1.03 (coal K). The ash content was the lowest in coal M (5.08%) and the highest in coal C (18.28%). SiO₂ was the dominant oxide form in ash, ranging between 48.76% (Coal J) and 75.78% (Coal A), which is typical for coal. Other major compounds in ash were Al₂O₃, CaO, and Fe₂O₃, but individual weight fractions widely varied between coals.

B. Measurement of cohesion strength

The coal samples in a particular size range was sprayed with to a target value of surface moisture content and stored in a sealed container for one day for sufficient permeation of the water. For measurement of cohesion strength, about 20-22 g of coal sample conditioned was compressed in a 1-inch diameter mold by a hydraulic press (Shimadzu UMH-30). Fig. 1 shows a schematic of the compression rig and the measurement of cohesion strength. After the target compressive force was maintained for one minute, the consolidated sample was removed from the mold by opening the screw cap on the top and pushing the piston through. The length of the sample was immediately measured to determine the density. The sample was then placed on a compression test machine (Instron 8841). The cohesion strength was determined as the compressive force at the failure of the consolidated sample after gradually increasing the force applied from the top. The tests were repeated at least twice for each test condition, and the average cohesion strength was calculated. The test method was based on the concept of the Edinburgh cohesion tester, but the mold diameter was reduced from 100 mm to 25 mm for easier testing with various coals and test parameters.

Table 2 lists the test parameters and conditions for evaluation of cohesion propensity. The compressive force was fixed at 150 kgf. This was because the cohesion strength increased linearly with the compressive force for two coals tested (Coals A and B with particle size of <1 mm and moisture added 9%), as shown in Fig. 2. The influences of surface moisture added (W_{added}) and particle size were tested for two coals (C and H). Note that W_{added} represents the relative weight of surface moisture sprayed over the air-dried sample. When testing the effect of particle size, three individual ranges of 0.1-0.5 mm (P#1), 0.5-1.0 mm (P#2), and 1.0-2.8 mm (P#3) and three mixtures (Mix #1-#3)

Table 2. Test parameters and conditions for cohesion properties of coal

Test parameter	Values	Tested coals
Compression force	150 kgf	
Surface moisture added	0(air-dried), 3, 6, 9, 12, 15, 18, 21 %	C, H
Particle size	[P#1] 0.1-0.5 mm, [P#2] 0.5-1.0 mm, [P#3] 1.0-2.8 mm, [Mix#1] P1 : P2 : P3 = 1 : 1 : 1, [Mix#2] P1 : P2 : P3 = 2 : 1 : 1, [Mix#3] P1 : P2 : P3 = 4 : 1 : 1,	C, H
Coal type	Particle size: P#1 (0.1-0.5mm), Surface moisture: 6, 9, 12, 15%	All coals

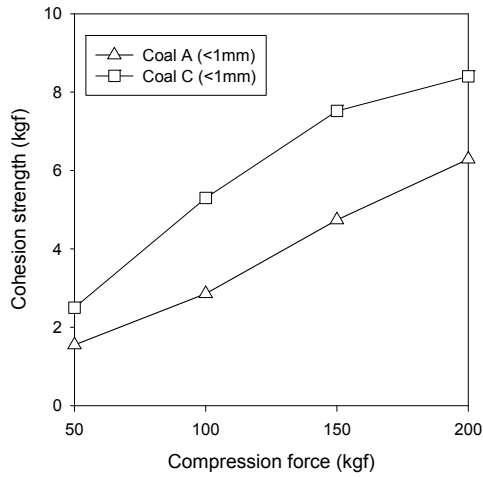


Fig. 2. Linear relationship of cohesion strength with compressive force.

were tested as given in the table. The particle sizes represented the lower range of coal sizes before pulverization. Particles larger than 2.8 mm have negligible cohesion propensity, if not mixed with fine particles. Particles after pulverization usually do not have cohesion problems since they are dried and transported by preheated primary air. The comparison of cohesion strength between coal samples was performed for P#1 that was the most cohesive. The surface moisture of the coals was controlled to 6, 9, 12 and 15%, considering the large variations in cohesion strength by moisture content.

III. RESULTS AND DISCUSSION

A. Effects of test parameters on cohesion strength

Fig. 3 shows the effects of moisture content for air-dried and wet samples up to 21% of surface moisture added. As also reported in the literature [8]-[10], moisture content is a crucial parameter of the cohesion strength. For coal C (Fig. 3(a)), the cohesion strength showed a bell-shaped trend with a peak value several times higher than that for the air-dried coals. As the particles became smaller, the peak of cohesion strength rapidly increased from 0.48 kgf (P#3) to 7.52 kgf (P#1). The coal with Mix#1 (1:1:1) exhibited the same trend, of which values were between those of P#1 and P#2. The critical moisture content for the peak value was about 9-12%. Note that the critical moisture content for P#1 was larger than the other size ranges, which was consistent with the study of Mikka & Smitham [8]. In their study using the Durham Cone test, the critical moisture content (expressed as total moisture) for a peak of the flow time increased from about 8% to 11% when a fraction of fines (< 0.5 mm) was added from 5% to 20%. For coal H in Fig. 3(b), the trend by different particle sizes was similar but the cohesion strength was

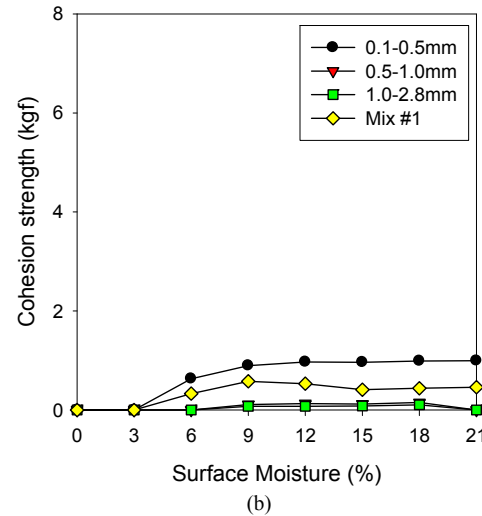
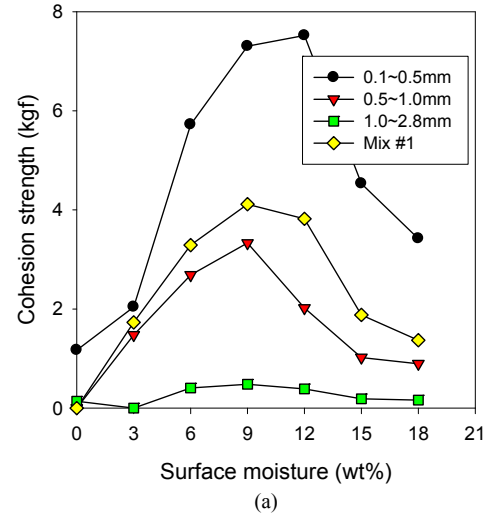


Fig. 3. Effects of moisture content and particle size on cohesion strength for coals C and H. (a) Coal C, (b) Coal H.

very low compared to coal C. In all size ranges of coal H, the consolidated samples with W_{added} of 0% (air-dried) and 3% barely maintained its cylindrical structure. This coal retained the weak cohesion (< 1.0 kgf) over a wider range of moisture content for particle P#1 and Mix#1.

Fig. 4 shows the change in the density of consolidated samples for coal C. The density gradually increased with W_{added} in all size ranges. This was because the presence of free water filled the voids between particles and helped rearrangement of particles under pressure by reducing friction, although the surface tension and capillary force of liquid bridges became weaker at larger values of W_{added} . The largest particles (P#3) had the lowest densities due to the larger voids between particles. In contrast, Mix #1 was the densest due to the fine particles effectively

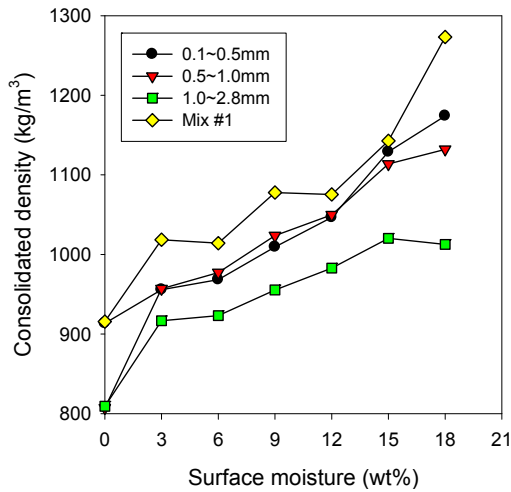


Fig. 4. Density of the consolidated samples for coal C.

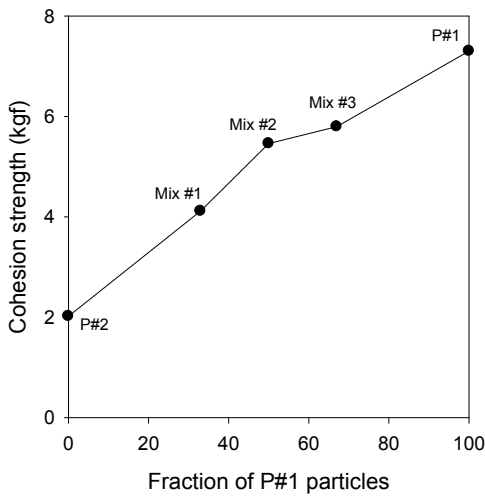


Fig. 5. Effects of fine particle fraction in a mixture on cohesion strength (Coal C, $W_{\text{added}}=12\%$).

minimizing the volume of voids. Such trends were similar for coal C, but its density was much lower (740 - 990 kg/m^3) than those of coal C. The relation of density and cohesion strength is further discussed later.

Fig. 5 shows the effect of fine particle fraction in a mixture for coal C for W_{added} of 12%. As the mass fraction of P#1 in the mixture increased from 0% to 100%, the cohesion strength showed a linear increase from 2.02 to 7.52 kgf. Therefore, the fraction of fine particles is another crucial parameter for cohesive coals, together with the surface moisture content.

B. Comparison of cohesion strength between coals

Based on the results for key test parameters, the cohesion properties of the coals were tested for particle size of P#1 (0.1-0.5 mm) with W_{added} of 6-15%. As shown in Fig. 6(a), the cohesion strength widely varied between tested coals. The coals in x-axis were arranged by the order of average cohesion strength. Coals A-D had the highest cohesion propensity, followed by coals E and F. In contrast, coals G and the rest had low cohesion strength (< 1.2 kgf) regardless of W_{added} . For the coals having certain cohesion propensity, the moisture content was the crucial parameter leading to variations as large as 7.8 kgf for coal D. The

results also show that the critical moisture content was different between coals. For example, coals A, C and F had a peak value of cohesion strength at W_{added} of 12%. However, the peak was at 15% for coals B and D which may have higher cohesion strength at a larger value of W_{added} . The trend of critical moisture content was not directly consistent with the coal properties including the inherent moisture content given in Table 1. This could be associated with the intra-particle pore volumes and microscopic surface area, which determine the capacity of internally absorbing the surface moisture added.

Fig. 6(b) shows the density of consolidated samples, which also had significant variations between coals. All the samples became denser with an increase in W_{added} , which was consistent with Fig. 4. The most loose sample was for Coal M (768 kg/m^3) at W_{added} of 6%, and the densest was Coal C (1129 kg/m^3) at 15%. Comparing the values with those in Fig. 6(a), the samples having a density above 900 kg/m^3 (coals A to G) had significant cohesion strength. This means that density could be used as an approximate measure for the cohesion propensity of coals, if compacted under identical test conditions (particle size, moisture content and compressive force). However, this cannot be applied to a particular coal in different conditions as shown in Figs. 3(a) and 4.

C. Relationship between cohesion strength and coal properties

Despite the considerable influence of the moisture content, it was difficult to find the critical moisture content and corresponding peak value of cohesion strength for individual samples. Assuming that the cohesion propensity of coals is represented by the average of the four values of W_{added} (the blue circles in Fig. 6(a)), its relationship with the coal properties was investigated using the data given in Table 1. However, no properties had a statistically meaningful correlation with the average cohesion strength since R^2 (the least-square from regression) was less than 0.45. In a study using Edinburgh cohesion tests for 19 Australian coals with -19 mm samples [13], the cohesion strength has been reported approximately proportional to the ash content of coal ($R^2=0.58$). For coals with different countries of origin in this study, the correlation was not statistically meaningful ($R^2=0.23$), as shown in Fig. 7(a). The best correlation among the coal properties was found for the inverse linearity with the CaO content in ash, as shown in Fig. 7(b), although R^2 was not sufficiently high (0.45).

Regarding the influence of ash, Mikka and Smitham [8] reported that the coal flowability depends on the types of clay minerals rather than on their amounts. Certain minerals such as bentonite swell on absorption of moisture. When up to 4.0 wt.% of bentonite was added to a test coal, the flow time (cohesion propensity measured using the Durham cone test) significantly increased in their study. In contrast, the addition of kaolin representing non-swelling clays did not lead to a rapid increase. Kaolinite, $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, typically consists of 14-42% on mineral matter basis, while montmorillonite, a key constituent of bentonite with a chemical formula of $(\text{Ca},\text{Na})_{0.3}(\text{Al},\text{Mg},\text{Fe})_2\text{Si}_4\text{O}_{10}(\text{OH})_2.n\text{H}_2\text{O}$ is about 0-4% [17]. Although not presented here, the mineral matter composition of the tested coals was analyzed by the X-ray diffraction method. The dominant minerals were kaolinite and quartz with trace amount of montmorillonite, illite, etc. However, no trend was found between the cohesion strength and kaolinite composition. Further detailed analysis is required to understand the relations between intrinsic coal

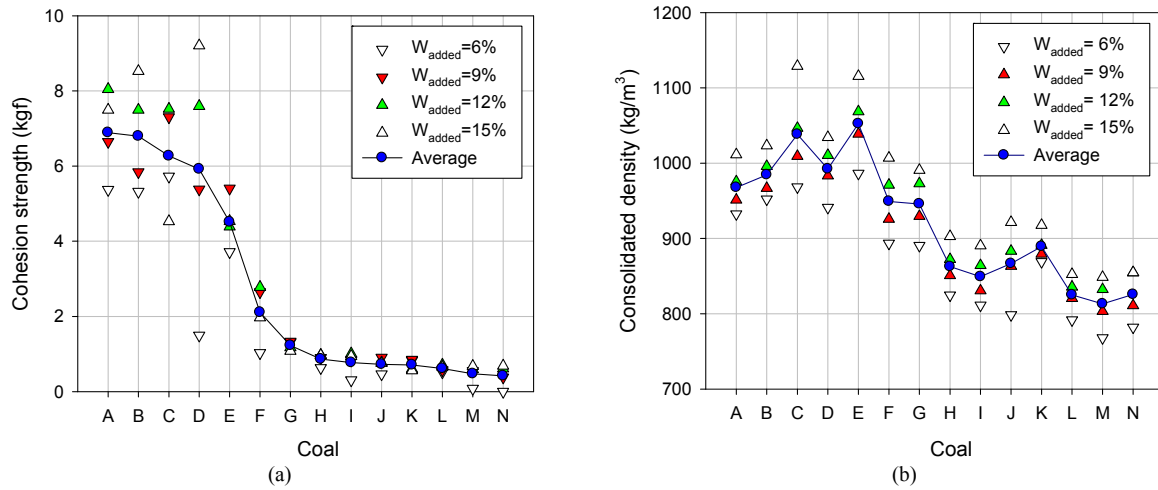


Fig. 6. Cohesion strength and consolidated density of various coals (size: 0.1-0.5mm). (a) cohesion strength, (b) consolidated density.

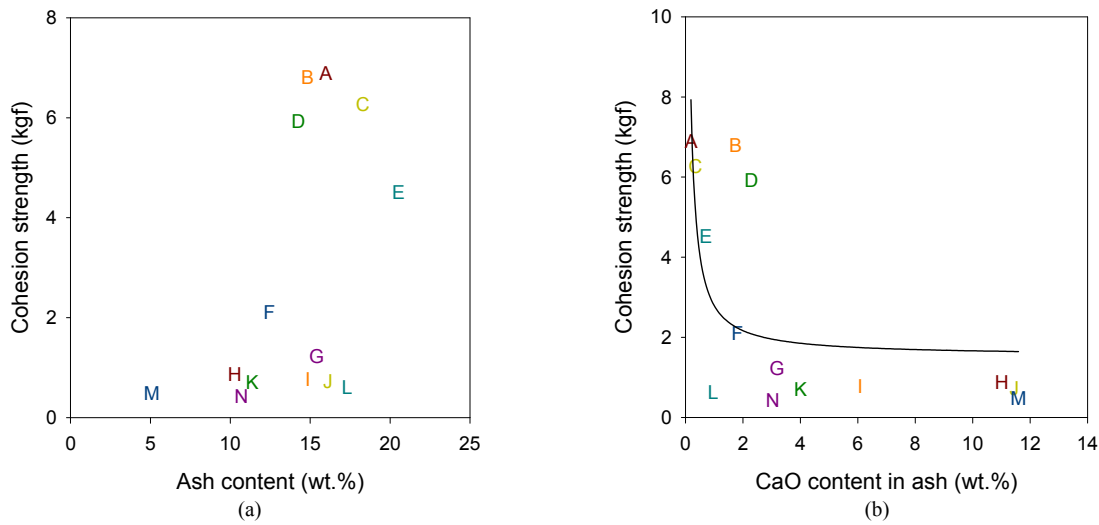


Fig. 7. Average cohesion strength vs. (a) the ash content of coal, (b) the CaO content in ash.

properties and the cohesion propensity.

IV. CONCLUSIONS

The cohesion properties of various coals were tested by measuring the force leading to the fracture of compressed particles with different size ranges (0.1-2.8 mm) and surface moisture added (0-21%). The cohesion strength was proportional to the compression force in the tested range. For cohesive coals, the effects of the surface moisture content and the proportion of fines were crucial. The surface moisture content had a critical value that maximized the cohesion strength. The cohesion strength was proportional to the mass fraction of fine particles (0.1-0.5 mm) in a mixture. At fixed tested conditions of surface moisture and particle sizes, large variations in cohesion propensity were found between coals. For coals of 0.1-0.5 mm with the moisture added close to the critical value, cohesive coals had the density over $900 kg/m^3$ after consolidation. The cohesion propensity was not directly correlated by the basic properties of coals (rank, inherent moisture, ash content and atomic composition). Although the statistical significance was not high, the best correlation was observed for CaO content which was inversely

proportional to the cohesion strength. Further studies are required for the influence of detailed coal properties on the cohesion propensity.

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