CHEMICAL ENGINEERING TRANSACTIONS
VOL. 32, 2013
Chief Editors: Sauro Pierucci, Jiří J. Klemeš
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ISBN 978-88-95608-23-5; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1332255

Characterisation of Flow Properties of Coal-Petcoke-Biomass Mixtures for Co-firing

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Solid biomass is often mixed with coal for cofiring in power plants to reduce greenhouse gases emissions. The resulting powder mixtures can give rise to handling and feeding problems due to the occurrence of intermittent flow or blockage. In this paper the flow properties of mixtures of a coal-petcoke powder and two types of biomass materials, dried olive husk (OH) and grape seed meal (GSM), were studied. The most significant effects on the cohesive properties of some powder mixtures were found for low biomass content mixtures due to their higher fraction of fine particles.

1. Introduction

Solid biomass is often mixed to traditional fuels like coal in co-combustion and co-gasification processes to reduce the fossil carbon dioxide emissions (Ruppolo et al., 2011) . This choice allows the use of existing plants without significant modifications in the energy conversion units if the proportion of biomass in the coal does not exceed 10% on energy basis. However, the industrial practice reports difficulties in handling and feeding this type of fuel mixtures due to the occurrence of irregular flow and stoppage. These problems are due to the change of the fuel flow properties caused by the addition of biomass granular solids. Handling and feeding issues can be affected also by these small concentrations of biomass. Characterisation of these mixtures can avoid malfunctioning of ancillary equipments that risks to seriously limit the reliability of the process and to cause uneconomical interruptions more often than in the thermal conversion units of the same plant (Dai et al., 2008). Also the knowledge of the flow properties (Miccio *et al*., 2009) and of the tendency to arching (Miccio *et al*., 2013) of biomass particulate solids alone is still limited. The effect of the presence of biomass on the flow properties of the blend was assessed by Zulfiqar *et al*. (2006) and by Khan *et al*. (2006) by using standard characterization instruments like shear testers. In these studies it was proved that the Jenike shear cell and annular shear cells could be suitable for coal-biomass mixtures with biomass blending ratios lower than 20% by weight. The effect of the addition of biomass to a coal powder on flow properties cannot be predicted without direct characterisation of the mixtures. In fact, Zulfiqar et al. (2006) reported that the addition of sawdust helps to reduce the strength of coal while maintaining similar frictional properties. Instead the addition of woodchips to coal had no effect on the unconfined yield strength but significantly impacted upon the frictional characteristics of mixture. Khan et al. (2006) highlighted that the moisture content of a coal-biomass mixture resulting from the moisture content of its components plays a significant role on the flowability of the blend, as it was observed for powders in shear flows (Landi et al., 2011) and in aerated conditions (Landi et al., 2012). Finally, also the particle size distribution of the mixtures has to be accounted for due to its effect on cohesive properties (Bruni *et al*. 2007) and on its aggregative behaviour (Barletta and Poletto, 2013).
In this paper the flow properties of mixtures of a coal-petcoke powder and two types of biomass materials, dried olive husk and grape seed meal, were studied. This work was carried out as part of a feasibility study on co-gasification with biomass for the Entrained Flow Gasification in Integrated Gasification Combined Cycle (IGCC) plants in the framework of the EU funded FECUNDUS project.

Please cite this article as: Barletta D., Diaz A., Esposito L., Montenegro L., Sanchez J.M., Poletto M., 2013, Characterisation of flow properties of coal-petcoke-biomass mixtures for co-firing, Chemical Engineering Transactions, 32, 1525-1530 DOI: 10.3303/CET1332255

2. Experimental apparatus and materials

2.1 Experimental apparatus and procedures

The Schulze Ring Shear Tester (RST), that was previously proved to be a suitable technique for finely ground biomass materials (Miccio *et al.*, 2011), was used in the laboratories of the University of Salerno to characterise the flow properties. The experimental procedure followed the international standard ASTM D6773 (2008) also described in textbooks (Schulze, 2008) and in the scientific literature (Tomasetta et al., 2011). Since the flow properties of powders and granular solids depend significantly on the consolidation state, it was necessary to estimate the range of stress values relevant for fuels stored in silos and bunkers of real co-gasification processes. The IGCC plant of ELCOGAS in Puertollano (Spain) was chosen as a reference. Geometrical configurations and dimensions of all storage units along the process (ground powder bunker, buffer vessels, lock hoppers, feed bins) after the grinding units were acquired from ELCOGAS. Typical consolidation stresses were evaluated according to the Janssen methods of differential slices for solid stresses in bin. As a result, the maximum consolidation stress, σ, at the bottom of the bin could be estimated as $\sigma = \rho_b g D$, where ρ_b is the powder bulk density, g is the acceleration due to gravity and D is the bin diameter. Lower consolidation stresses of a few kPa can be experienced by the powder in the vicinity of the hopper outlet whose size can be of the order of 1 m. As a result, a consolidation stress range between about 4 and 40 kPa was chosen for the characterization of powder flow properties by means of shear tests. Therefore, shear cells of different size, named M and S, (internal volume 940 and 200 cm^3) were used in the RST to cover the selected wide range of consolidation stress.

2.2 Materials

The reference material was a mixture of Puertollano coal and petroleum coke (50% by weight), CP, currently used as fuel feed in the IGCC plant of Elcogas. The biomass samples to be added to the coal-petcoke mixture were olive husk, OH, and grape seed meal, GSM. This choice was based on the following requirements: 12-15% initial moisture content; particle size before grinding less than 25 mm; heating value and ultimate analysis close to that of fossil fuels; cost less than 100 €/t; biomass availability in large quantities. Ternary mixtures formed by the original coal-petcoke fuel and increasing amounts (2, 4, 10 and 20% by weight) of one of the two biomass samples were prepared. In the industrial process all the fuel streams are fed to a mill to reduce the particle size and then to a dryer to make the powder moisture decrease. As a result, a similar procedure was followed in the laboratories to reproduce the industrial mixture characteristics in terms of moisture and particle size distribution. In particular, the samples were prepared by mixing the coarse coal-petcoke mixture with the coarse biomass sample. These samples were first dried at 105°C for 24h and then ground with two passes in a jaw crusher Retsch BB51 (1100W) in the CIEMAT laboratories to reproduce the fuel characteristics of the industrial process in terms of moisture and particle size distribution.

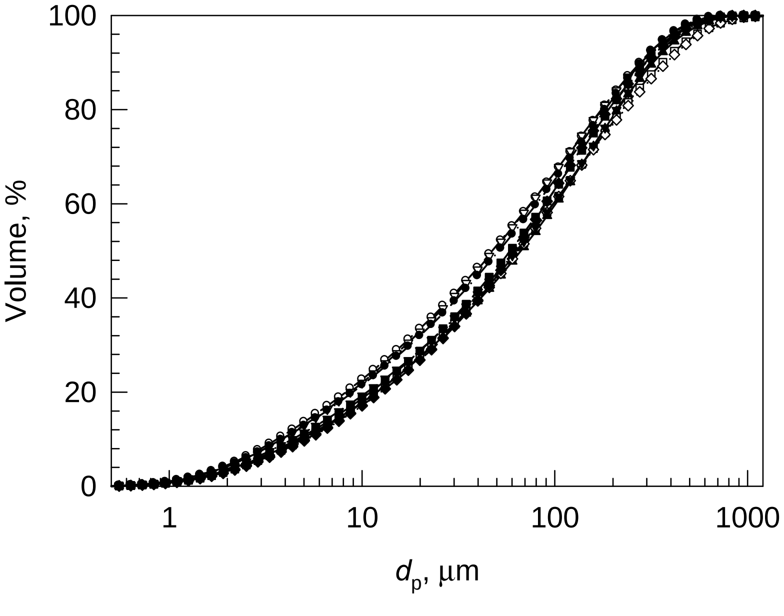

Figure 1: Cumulative particle size distribution by volume : ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

Table 1: Particle size distribution and moisture content of fuel mixtures

Mixture	Coal [wt%]	Petcoke [wt%]	GSM [wt%]	OH [wt%]	d_{pS} [µm]	d_{p10} [µm]	d_{p50} [µm]	d_{p90} [µm]	X_w [wt%]
CP	50	50	0	0	12.9	4.8	66.7	322.4	1.7
OH-2%	49	49	0	2	10.8	3.8	51.3	280.3	1.7
OH-4%	48	48	0	4	12.1	4.4	63.0	313.0	1.8
OH-10%	45	45	0	10	12.4	4.6	58.8	294.9	1.5
OH-20%	40	40	0	20	13.4	5.1	61.8	297.8	1.8
GSM-2%	49	49	2	0	10.3	3.6	47.3	276.1	1.6
GSM-4%	48	48	4	0	10.7	3.8	48.0	280.0	1.5
GSM-10%	45	45	10	0	13.3	5.0	64.1	361.7	2.2
GSM-20%	40	40	20	0	13.7	5.2	64.8	378.6	2.2

Volumetric particle size distributions of the obtained powders were measured in water with Nonidet dispersing agent by means of a Malvern Mastersizer 2000. Moisture weight fractions in the samples, X_W, were measured with an Ohaus gravimetric tester.

3. Results

The measured cumulative particle size distributions by volume are reported in Figure 1. The characteristic size values derived from the distributions, namely the Sauter mean size, d_{pS}, the 10th, 50th and 90th percentile size, d_{p10}, d_{p50}, d_{p90}, are reported in Table 1. Biomass addition by less than 5% causes a slight decrease of the value of all the characteristic size due to larger generation of fines in the grinding process. Conversely, the mixtures with 10% and 20% of GSM have d_{pS}, d_{p10} and d_{p50} values closer to those of the CP mixture while the d_{p90} value is larger due to the presence of coarser particles.
The shear tests gave very repeatable experimental points of the yield loci at different consolidation stresses. The yield loci curves were regressed from experimental points by straight sections approximation. Main flow properties at failure (cohesion, static angle of internal friction, effective angle of internal friction, unconfined yield strength, bulk density) were derived from the yield loci by the Mohr analysis. These properties are reported as a function of the major principal stress in Figures 2 to 6 for the coal-petcoke mixture and for the ternary mixtures of coal-petcoke with olive husk and grape seed meal (2%, 4%, 10% and 20% by weight).

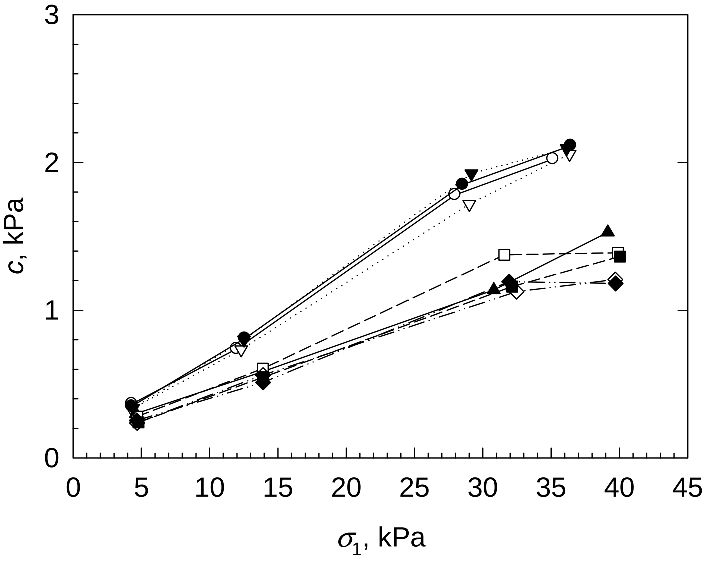

Figure 2: Cohesion as a function of the major principal stress: ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

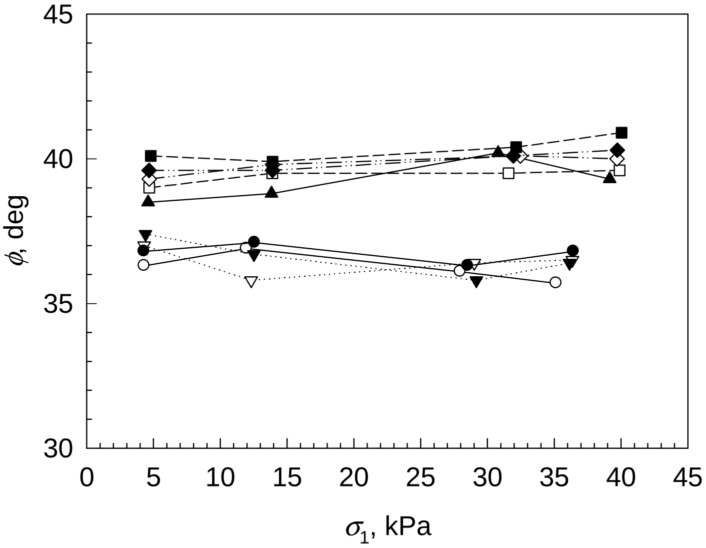

Figure 3: Angle of internal friction as a function of the major principal stress: ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

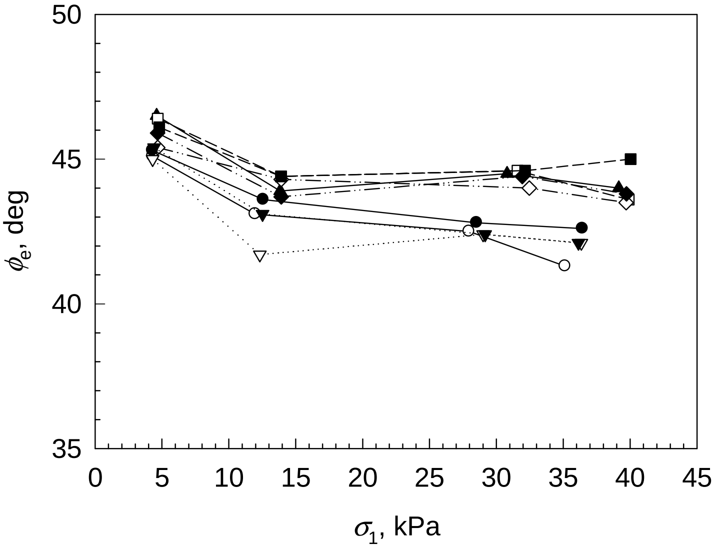

Figure 4: Effective angle of internal friction as a function of the major principal stress: ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

In general, the addition of biomass to the original coal-petcoke powder has a different effect on flow properties depending on the biomass weight content. In particular, low biomass concentration (2% and 4%) seems to affect more significantly the flow properties of the mixtures. Figure 2 reveals that the cohesion, c, increases for mixtures with 2% and 4% of GSM and of OH with respect to the CP mixture, while it is substantially unchanged for mixtures with 10% and 20% of GSM. In particular, the cohesion increment for 2% and 4% biomass mixtures is more significant for increasing values of powder major consolidation stress, σ_1 (up to a 40% increase with respect to the CP mixture). Negligible differences appear between the results of the mixtures with the two types of biomass for a given biomass content. The plots of the static angle of internal friction, ϕ, (Figure 3) indicates that a low content (2% and 4%) of GSM or OH is beneficial to decrease the internal friction of the powder. The mixtures with higher GSM content do not exhibit significant changes of ϕ with respect to the CP mixture. Similarly, Figure 4 shows that the effective angle of friction, ϕ_e, decreases for mixtures with 2% and 4% of biomass, while it is unchanged for

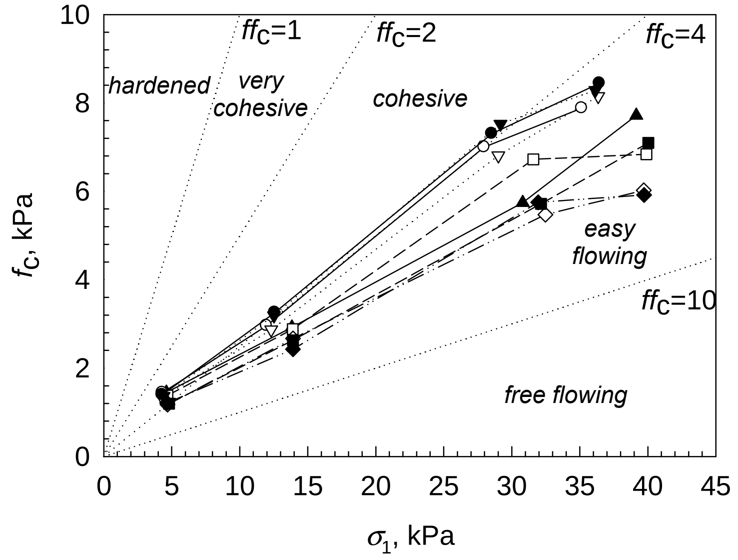

Figure 5: Unconfined yield strength as a function of the major principal stress: ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

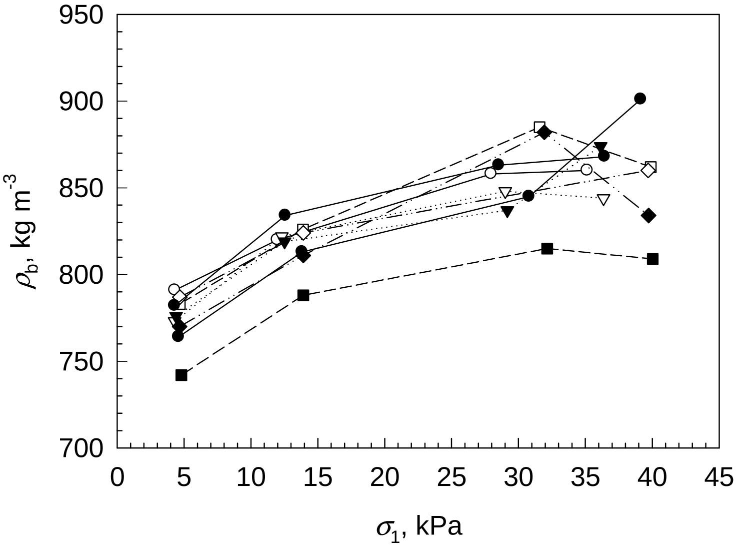

Figure 6: Bulk density as a function of the major principal stress: ▲, CP; ●, OH-2%; ▼, OH-4%; ■, OH-10%; ◆, OH-20%; ○, GSM-2%; ▽, GSM-4%; □, GSM-10%; ◇, GSM-20%.

the 10% and 20% GSM mixtures. Flow functions (unconfined yield strength, f_c, as a function of major principal stress σ_1) of all tested mixtures are reported in Figure 5. According to the flowability classification proposed by Jenike (1964) in terms of flow factor, ff_c, the coal-petcoke mixture and the ternary mixtures 10% and 20% GSM are easy flowing powders ($4<ff_c<10$) with comparable values of f_c. Differently, the mixtures with 2% and 4% of either GSM or OH show higher f_c. As a result, corresponding flow functions lay in the region of the cohesive powders ($2< ff_c <4$). This increase of the unconfined yield strength seems to be due to the prevailing effect of the cohesion increase on the decrease of the static angle of internal friction. This observation is further supported by the increasing difference between f_c values of the ternary mixtures and those of the CP binary mixture with increasing σ_1. An increasing relative difference can be observed also for the cohesion *c* with increasing σ_1. Small variations of the average bulk density between the mixtures (Figure 6) do not seem to be related to the change of flow properties. Neither the moisture content X_w values reported in Table 1 can justify the different cohesive and frictional properties of the mixtures. A possible cause for the increase of cohesive properties for the 2% and 4% biomass mixtures can be found in their particle size distribution. In fact, the particle size distribution of the mentioned ternary mixtures is characterised by finer particles with respect to the coal-petcoke powder and the ternary mixtures with higher biomass content (10% and 20%). The decrease of friction for the low biomass content mixtures could also be explained by a lubrication effect of the fine particles or by possible differences in particle shape of coal, petcoke and biomass. In order to shed light on this point, SEM images were taken for all the powders. However, inspection of the images did not reveal any significant difference.

4. Conclusions

The addition of small amount (2%-4%) of biomass particles to a coal-petcoke mixture before grinding causes an increase of the volumetric content of fine particles. This change in the particle size distribution results in a significant increase of the cohesion and of the unconfined yield strength of these powders in spite of a slight decrease of the angle of internal friction. These results indicate that the discharge flow regime (mass flow or funnel flow) in hoppers designed for the coal-petcoke mixture should remain substantially unchanged when adding the tested biomass samples. Differently, higher unconfined yield strength might more likely cause the occurrence of cohesive arching. Larger amounts of biomass particles (10%-20%) do not determine significant changes of the particle size distribution and of the powder flow properties with respect to the original coal-petcoke powder. Therefore, the flow behavior of these mixtures should not negatively affect the reliability of the handling operations in the industrial process.

Acknowledgements

The research was funded by the European Commission - Research Fund for Coal & Steel (FECUNDUS project grant agreement n. RFCR-CT-2010-00009). Dr. Pilar Coca Llano of Elcogas (Spain) is acknowledged for providing the raw materials and information about industrial storage units.

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