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Characterization of the flowability of fly ashes from grate-fired combustion of forest residues

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ABSTRACT

Data about the flowability of fly ashes are important for the design of hoppers of fly ash collection equipment and fly ash storage silos. Fly ashes from sixteen grate-fired combustion plants (first-stage and second-stage de-dusting fly ash) were examined for flow relevant properties. The flowability category of the coarser first-stage fly ashes was cohesive to easy-flowing, while for the second-stage fly ashes the flowability category was very cohesive to cohesive. A good correlation was found between the flowability of the fly ashes and the mass median diameter of their particle size distribution. The correlation of the flowability with the bulk density or with the angle of repose was less significant. No correlation was found with the other parameters investigated. Moreover, the effective angle of internal friction, the wall friction angle and bulk density can be expressed as a function of the mass median diameter. Thus, the particle size is the most important parameter for the flowability of the fly ashes.

1. Introduction

Concerns about climate change caused by the carbon dioxide emissions from fossil fuel combustion have given rise to combustion of biomass for heat and power generation [1]. Biomass combustion is considered to have almost no impact on carbon dioxide emissions because the carbon dioxide emissions produced in the combustion process are compensated by the carbon dioxide fixed during growth of the biomass. In Austria nearly 80% of the biomass-based energy is derived from wood [2]. Forest residues, saw mill residues and bark account for approximately half of this energy. For small and medium size combustion systems grate-fired combustion is usually applied [3].

Combustion of biomass generates a considerable amount of ash which consists of the inorganic matter contained in the biomass plus a small fraction of unburnt carbon and organic matter. While most of the ash from grate-fired combustion is discharged as bottom ash (75–90%), the fine fraction of the ash leaves the combustion zone as fly ash together with the flue gas [4]. The fly ash has to be separated from the flue gas in a dust collector. In order to comply with low dust emission limits, usually electrostatic precipitators (ESPs) are used as fly ash collectors. The collection efficiency of inertial separators, like cyclones, is limited, especially for fine particles. Dust collection by a cyclone is sufficient for smaller biomass combustion plants only because of higher dust emission limits. However, a cyclone is often used as a pre-separator upstream of the ESP in two-stage dust collection systems.

The chemical composition of biomass fly ashes has been investigated widely [4–13], but data of the physical properties of fly ash are rare. Values for the particle density and the bulk density of different biomass fly ashes have been reported [5–7]. Some results from particle size distribution measurements are also available [8,9,14], but only few data are available for the flow properties of fly ash from biomass combustion [14]. Results for the angle of repose for various fly ashes from biomass combustion are available in [6,7], which can be used as an indicator for the flowability characterization [15]. However, for the dusts from various other industrial de-dusting systems it has been shown that the angle of repose and other easy-to-determine flow indicators often overestimate the flowability of the fine-grained dusts [16–18].

Knowledge of the flow properties of fly ash is required for proper design of fly ash storage silos, hoppers of fly ash collection installations and other fly ash handling equipment so that no flow problems occur [19]. For the design calculations, the flow function (unconfined yield strength σ_c as a function of the consolidation stress σ_1), the effective angle of internal friction φ_e, the wall friction angle φ_w and bulk density ρ_b, as a function of the consolidation stress, are required [19–21]. These properties can be measured using a shear tester.

The aim of this study is to characterize the flowability of fly ashes from grate-fired forest residue combustion plants. Fly ash samples collected from several combustion plants were tested using a ring shear tester. Additionally, the particle size distribution and other properties of the fly ashes: the humidity, the bulk density, the angle of repose and the total carbon content, as a measure of the quality of the combustion, were determined. Thus, the influence of various parameters on the behaviour of the fly ashes can be investigated.

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2. Methods

2.1. Sample collection and sample preparation

Fly ash samples from sixteen grate-fired biomass combustion plants were collected for this study. In all combustion plants forest residues were used as the main fuel. In some plants a small fraction of sawmill residues and bark was used additionally. The thermal capacities of the plants and the type of off-gas cleaning system installed are summarized in Table 1. From plants with a two-stage off-gas cleaning system fly ash samples were collected from both stages, if possible. However, in several plants the fly ash from the cyclone pre-separator is not discharged separately but discharged together with the bottom ash. Fly ash samples of approximately 2 dm^3 were collected at the discharge outlet of the dust collectors. The volume of the ash samples was reduced to a volume suitable for the various laboratory tests using sample dividers which were applied repeatedly (Haver RT 12.5, Quantachrome Micro Riffler).

2.2. Measurement procedures

The moisture content of the fly ash samples was determined gravimetrically. The samples were dried at 105 °C for 1 h.

The total carbon (TC) content of the fly ashes was measured using an Elementar Analysensysteme LiquiTOC system with a solids material extension. By combustion with air all carbon is transformed into CO_2, which is subsequently analyzed. The system was calibrated using a soil standard from Elementar Analysensysteme with 4.1% TOC/TC.

The particle size distribution of the fly ashes was determined using a laser diffraction instrument with dry sample dispersion from Sympatec, type HELOS/RODOS. The calibration of the instrument was verified with a SiC-P600'06 standard from Sympatec. The target value for the mass median diameter x_{50} is 25.59 μm and the acceptable range is 24.82 μm to 26.36 μm. The measured value for the x_{50} was 25.62 μm.

The spread of the particle size distribution was calculated as the quotient of x_{90} and x_{10} [22]. The x_{10} is the particle size with 10% of the mass of the material consisting of particles smaller than this size and 90% of the mass of the material consisting of larger particles. The x_{90} is defined in a similar way.

The bulk density of the fly ash samples was determined according to ÖNORM EN ISO 60 [23]. For such a measurement the bottom cover of the funnel is removed which lets 120 cm^3 of powder stored in the funnel flow by gravity into the coaxial measuring cylinder. The volume of the certified measuring cylinder is 100 ± 0.5 cm^3. The excess material is removed by drawing a straightedge blade across the top of the vessel.

Table 1
List of fly ashes investigated.

Plant	Thermal capacity in MW_{th}	Off-gas de-dusting system	
		First stage	Second stage
Single stage de-dusting system			
A	0.5	Baffle separator	–
B	0.5	Baffle separator	–
C	1.0	Multi-cyclone	–
D	1.1	Cyclone	–
E	3.0	Multi-cyclone	–
F	3.0	Multi-cyclone	–
Two-stage de-dusting system			
G	1.5	Multi-cyclone; no sample available	ESP
H	2.0	Multi-cyclone	ESP
J	2.0	Multi-cyclone; no sample available	ESP
K	2.0	Multi-cyclone	ESP
L	3.0	Multi-cyclone	ESP
M	3.5	Multi-cyclone; no sample available	ESP
N	4.0	Multi-cyclone; no sample available	ESP
O	10	Multi-cyclone; no sample available	ESP
P	10	Multi-cyclone; no sample available	ESP
Q	25	Multi-cyclone	ESP

The yield locus for the fly ash samples was determined using a RST-XS Schulze ring shear tester with a 30 cm^3 shear cell. For a shear test the fly ash sample is loaded vertically via the cover of the shear cell at a certain normal stress, then a shear deformation is applied to the fly ash sample by moving the shear cell at a constant velocity resulting in a horizontal shear stress in the sample. Each point of a yield locus is measured in two steps. In the first step, the pre-shear step, the sample is consolidated. Here the point of steady-state flow with the pair of values for the normal stress σ, the shear stress τ and the bulk density are determined. In the second step, a point of the yield limit is measured at a reduced normal stress. The corresponding pair of values for the normal stress and the shear stress at a point of incipient flow is one point of the yield limit. The whole yield locus is determined by repetition of the procedure. A Mohr stress circle, which runs through the point of steady-state flow and is tangential to the yield locus, can then be drawn. The slope of a tangent to this stress circle which runs through the origin of the σ-τ-diagram represents the effective angle of internal friction [19]. The test procedure was conducted at six values of the normal stress (600 Pa, 1200 Pa, 2500 Pa, 5000 Pa, 10,000 Pa and 20,000 Pa) as described.

The calibration of the shear tester was verified at a normal stress of 3000 Pa at pre-shear using the certified reference material BCR-116 from the Community Bureau of Reference (Limestone Powder), which was also used in a round robin test on ring shear testers [24]. The measured values of the shear stress were in the range of the reported mean shear stress $\tau_m \pm 0.6$ times the reported standard deviation s.

The wall yield locus for the fly ash samples was determined using a RST-XS Schulze ring shear tester with a wall friction shear cell. In this cell the bottom ring is formed by a sample of the wall material which was structural steel S235JR (1.0038). For a shear test, the fly ash sample is loaded vertically at a certain normal stress and is then moved in relation to the wall material surface at a constant velocity. To measure a point of the wall yield locus corresponding pairs of values for the normal stress and the shear stress are determined. Wall friction angle measurements were performed at six values of the wall normal stress (600 Pa, 1200 Pa, 2500 Pa, 5000 Pa, 10,000 Pa and 20,000 Pa). The kinematic angle of wall friction is the slope of a straight line running through the origin of the σ-τ-diagram and a point of the wall yield locus [19].

2.3. Numerical characterization of flowability

A quantitative characterization of the flowability of a bulk solid is possible by the factor ff_c which is the ratio of consolidation stress σ_1 to unconfined yield strength σ_c [25]. The consolidation stress is equal to the major principal stress of the Mohr stress circle which runs through the point of steady-state flow and is tangential to the yield locus. The unconfined yield strength results from the stress circle that runs through the origin and is tangential to the yield locus [20]. The higher ff_c is, the better a bulk solid flows. The usual classification to define flow behaviour is: not flowing: $ff_c < 1$; very cohesive: $1 < ff_c < 2$; cohesive: $2 < ff_c < 4$; easy-flowing: $4 < ff_c < 10$, and: free-flowing: $10 < ff_c$ [25].

The flowability of a bulk solid depends on the consolidation stress. For most bulk solids better flowability will be obtained at a greater consolidation stress. Due to this dependence it is not possible to describe the flowability of a bulk solid with only one numerical value. A good visualization of the flowability can be given in a diagram with logarithmic scaled axes showing the unconfined yield strength dependent upon the consolidation stress, when the diagram also includes lines of constant ff_c ratio [26].

3. Results

3.1. Fly ash particle size distributions

The particle size distributions of the first-stage and the second-stage fly ashes are summarized in Fig. 1. The mass median diameters of the fly