ELECTRIC ARC FURNACE DUST: CHARACTERIZATION OF FLOWABILITY

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https://doi.org/10.37904/metal.2023.4626

Abstract

Considerable amounts of dust are generated as by-product in electric arc furnace (EAF) steel production. Dry off-gas de-dusting systems, usually dust filters are used to collect these dusts from the off-gas. In the design and operation of storage and transport equipment for the collected dusts the flow properties of the dusts play an important role. The properties relevant for particle flow – angle of internal friction, wall friction angle, bulk density and time consolidation - of EAF filter dusts originating from eight steel mills were investigated. The results showed significant differences between the EAF dusts from different steel mills. The variations of the various parameters are shown and some consequences for the design of EAF dust silos and filter hoppers are discussed.

Keywords: Steel mill, electric arc furnace, dust storage, flow properties

1. INTRODUCTION

In the production of steel in mini mills by smelting of scrap and direct reduced iron in an electric arc furnace (EAF) significant amounts of dust are produced. According to the “Best Available Techniques (BAT) Reference Document for Iron and Steel Production” the range of dust produced in EAF steelmaking is 10 kg to 30 kg of dust per ton of liquid steel [1]. Most of the dust is contained in the primary off-gas, which is extracted from the furnace via a hole in the furnace roof. The coarse fraction of this dust is usually separated by a pre-separator, e.g. a drop-out-box situated near the EAF while the fine dust fraction stays in the off-gas during off-gas cooling. The secondary dust emissions which are generated during charging and tapping operation, as well as fumes escaping from furnace openings are captured by a canopy hood located above the furnace. In most mini mills the cooled primary off-gas and the secondary off-gas are mixed before final dedusting by a fabric filter [2,3]. For undisturbed plant operation the EAF dust collected in the fabric filter has to be discharged safely from the filter hoppers and subsequently conveyed to the storage silo. Proper discharge from the storage silo is also required.

For a general characterization of the flow properties of a dust the angle of repose [4] or the flowability ff_c [5] can be used. ff_c is the ratio of the consolidation stress to the unconfined yield strength. The larger the value of ff_c, the better a dust flows. However, for the reliable design of filter hoppers and silos using the design method according to Jenike [6], more detailed information on the dust properties is required: the yield locus, the wall friction angle and the stress dependence of the bulk density of the dust [7]. Some dusts gain in strength over time when they are stored under a compressive stress. This behavior is called time consolidation or caking and results from the increase of interparticle adhesive forces with time based on different mechanisms. If the dust particles are moved relative to each other, these adhesive forces diminish and during further storage at rest they build up again. Therefore, the time yield locus of the dust is also required if the dust has to be stored for some time in the hopper or silo.

Hardly any information on flow properties of EAF dust is available in literature. One study states that EAF dust is very cohesive and reports some data on measured yield locus, stress dependence of the bulk density and wall friction angle [8]. In another study [9] the influence of organic matter content in EAF dust on bulk density and flowability was investigated. With respect to time consolidation of EAF dust no information was found. The aim of this study was to investigate the range of variation of flow characteristics of EAF dust as well as the occurrence of time consolidation in EAF dust.

2. MATERIALS AND METHODS

2.1 Materials

EAF dust samples from eight mini mills of approximately 1-2 dm³ each were collected at the discharge systems of the fabric filters or at the storage silos (samples A to H). In the laboratory, the quantity of the EAF dust samples was reduced to a volume suitable for the laboratory tests using sample dividers (Haver&Boecker HAVER RT, Quantachrome Micro Riffler).

2.2 Methods

The moisture content of the EAF dust samples was measured gravimetrically using a Sartorius infrared moisture analyzer MA35M at 110 °C. The results reflect the equilibrium moisture content at laboratory atmosphere conditions.

The angle of repose of the EAF dust samples was determined according to the standard ISO 4324 [10]. A cone of material is heaped up by directing the powder through a special funnel which is placed at a defined height above a horizontal and flat circular plate. The base angle of the cone is calculated from the diameter of the base plate and the height of the cone.

The bulk density of the EAF dusts was measured according to EN ISO 60 [11]. The bottom cover of a funnel is removed to allow 120 cm^3 of dust stored above to flow into a coaxial 100 cm^3 measuring cylinder by gravity. The excess dust material is removed with a blade from the measuring cylinder before the weight is determined.

The yield locus, the stress dependence of the bulk density and time consolidation of the dusts were determined using a Schulze RST-XS ring shear tester [12,13] with a 30 cm³ shear cell. The shear tests were performed at three values of normal stress: 600 Pa, 2000 Pa and 6000 Pa. The wall friction angle of the material was also determined with the shear tester using a wall shear cell containing structural steel S235JR as wall material.

Time consolidation measurements are quite time-consuming. Therefore, it is the common practice to determine only one shear point of the time yield locus of a dust. The time yield locus is then approximated by a parallel to the linearized yield locus running through the measured shear point [14,15]. In the measurements the shear point was determined with a normal stress of 2000 Pa. Time consolidation can also occur between the dust and the wall material.

3. RESULTS AND DISCUSSION

3.1 Flow properties

Table 1 summarizes some of the measured results. Generally, notable differences between the various EAF dust samples were found. The moisture content of the dusts was in the range of 0.4 to 1.9% and the angle of repose varied between 41° and 49°. According to the measured angle of repose [16] the flow characteristics of EAF dusts A, C and G is "passable" (41° to 45°) while for the other EAF dusts it is "poor/cohesive" (46-55°). The flowability ff_c calculated from the consolidation stress and the unconfined yield strength measured at low stress leads to a quite different classification. The EAF dust A, E and H are classified as "cohesive" ($2 < ff_c < 4$) while the others ear classified as "very cohesive" ($1 < ff_c < 2$) [5]. This difference can be explained by the formation of dust agglomerates formed during the measurement of the angle of repose which roll visibly down the slope of the dust cone thereby flattening the angle of the cone. Such an effect has been reported previously for fine dust from a copper mill [17]. Consequently, no correlation between the angle of repose and the flowability ff_c could be found. Other authors have also stated that for characterization of dust flow properties results from measurements of the type described in ISO 4324 are to be used with caution [18].

While the angle of repose is measured under conditions with no stress at the surface of the dust the flowability ff_c can be determined for varying stress conditions in the dust. **Figure 1** shows ff_c as a function of the consolidation stress. Generally, the flowability improves with increasing consolidation stress. This improvement was found to be higher for EAF dusts with better flowability.

Table 1 Data of EAF dust samples at low stress

EAF dust samples	Moisture content (wt%)	Angle of repose (°)	Flowability ff_c^1	Effective angle of internal friction^1 (°)	Wall friction angle^1 (°)	Hopper slope angle at the mass flow boundary^2 (°)
A	0.19	42	2.8	45	25	19
B	0.95	47	1.2	64	31	13
C	0.40	41	1.4	58	32	11
D	1.2	46	1.3	53	30	13
E	1.9	49	2.3	45	27	18
F	1.8	47	1.8	56	29	15
G	0.44	42	1.1	69	33	10
H	1.5	47	2.6	45	28	16

^{1}measured at a normal stress of 600 Pa

^{2}for conical hoppers, no safety margin considered

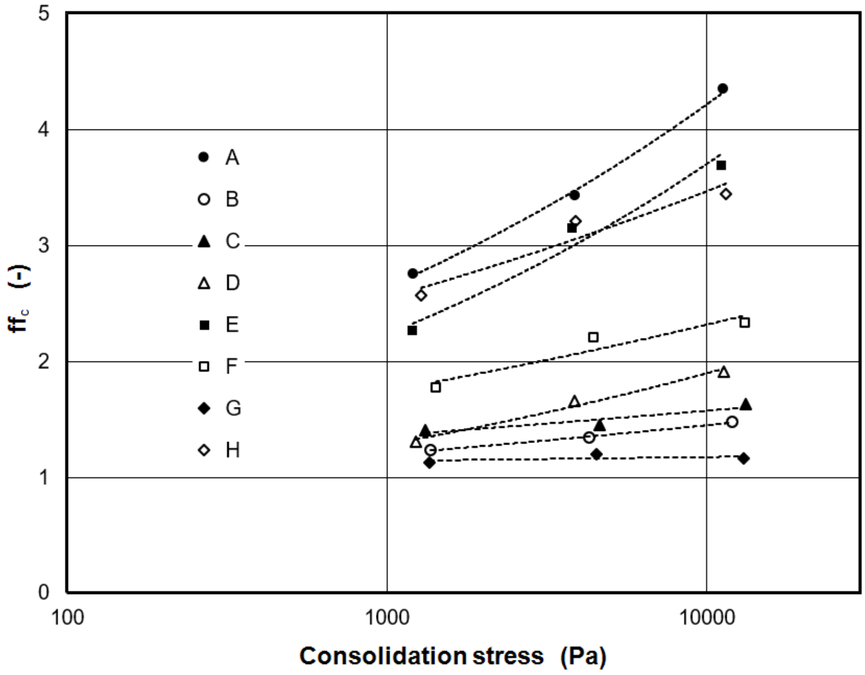

Figure 1 Flowability ff_c of various EAF dusts as a function of the consolidation stress

From the effective angle of internal friction and the wall friction angle the hopper slope at the boundary between mass flow and funnel flow in the silo can be derived using the respective diagram established by Jenike [6,14].

The resulting hopper slope angles for the various EAF dusts varied between 10° and 19°. In real silo design a safety margin of 2° to 3° should be considered which reduces the hopper slope angle for mass flow accordingly [14]. However, EAF dust silos and filter hoppers are usually not designed with such a steep cone. Therefore, funnel flow has to be expected in the hoppers, where stagnant zones or dead zones occur starting directly above the bottom opening or at the height at which the effect of an installed discharge aid ceases. Dust from these zones can be discharged only if the hopper is emptied completely.

At low consolidation stress the values of the effective angle of internal friction were in the range of 45° to 69° and the values of the wall friction angles ranged from 24.8° to 33.0° (**Figure 2**). Both, the effective angles of internal friction as well as the wall friction angles decreased with increasing consolidation stress. The available literature data for EAF dusts [8,9] show a similar behavior.

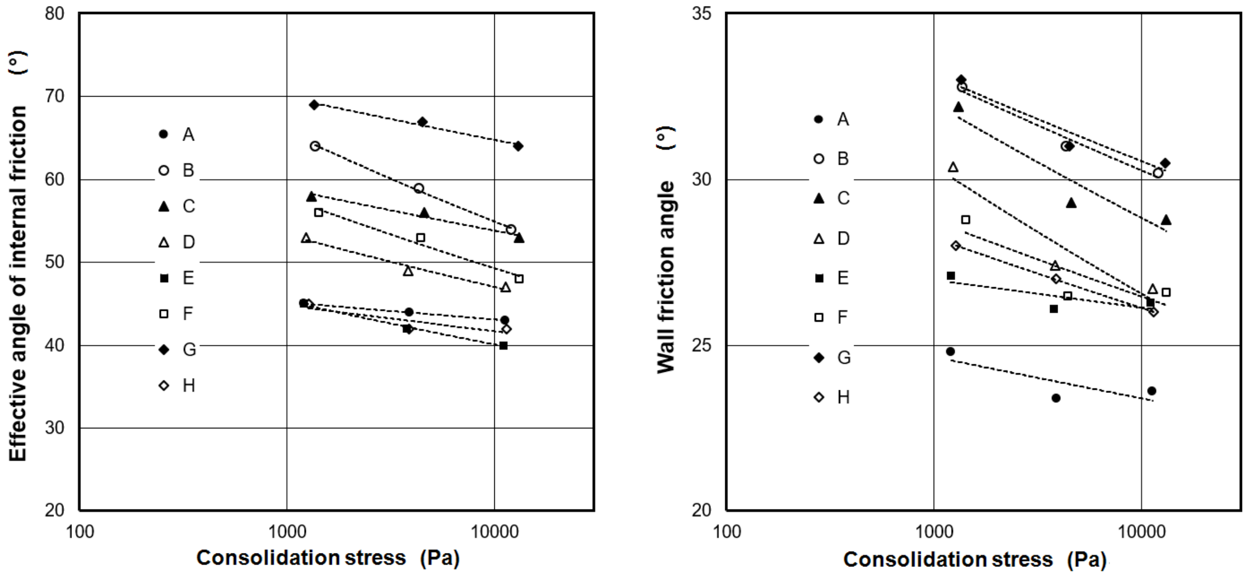

Figure 2 Effective angle of internal friction (left) and wall friction angle (right) of various EAF dusts as a function of the consolidation stress

3.2 Bulk density

The results measured for bulk density are summarized in **Table 2**. The values of the bulk density according to EN ISO 60 were in the range from 862 kg/m³ to 1099 kg/m³. Since the bulk density is also strongly dependent on the consolidation stress a higher density must be taken into account both in mass storage capacity design and in load calculation, in addition to the strong variance of the values. The relation between the bulk density and the consolidation stress can be expressed very well by a power function [19] (Eq. 1),

$$\rho_b = K.(\sigma_1/\sigma_0)^c \tag{1}$$

where:

ρ_b – bulk density (kg/m³);

σ_1 – consolidations stress (Pa);

σ_0 – reference stress 1 Pa;

K – constant (kg/m³);

c – exponent (-).

This function has been used in literature to describe the relation between bulk density and consolidation stress for various powders [20]. The exponent of the power function characterizes the compressibility of the dust.

Table 2 Bulk density of EAF dust samples

EAF dust samples	Bulk density EN ISO 60 (kg/m³)	Parameters of the power function	
		Constant K (kg/m³)	**Exponent c**
A	1099	749	0.055
C	973	459	0.102
D	1052	468	0.107
E	982	660	0.064
F	958	643	0.064
G	862	394	0.116
H	950	626	0.063

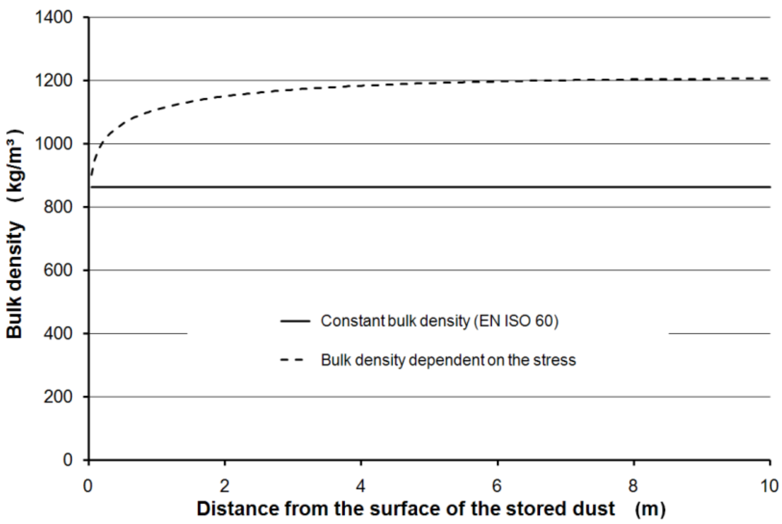

Figure 3 Bulk density of EAF dust G as a function of the height

In combination with the equation of Janssen modified for stress dependent bulk density according to [20] the bulk density of the dust in a silo can be calculated as a function of the height of the silo. **Figure 3** shows the result exemplarily for a silo with a cylindrical height of 10 m and an inner diameter of 5 m. The calculated average density of the dust for the shaft of the silo is 1234 kg/m³ which is considerably higher than the bulk density measured according to EN ISO 60. This has to be considered e.g. in the static design of the silo.

3.3 Time consolidation

The time yield locus was determined for the four EAF dusts E, F, G and H. For all four of them the flowability ff_c decreased with the time of storage under stress during the first three days. After this storage time the flowability stayed constant (**Figure 4**). Therefore, time consolidation has to be considered in design of EAF dust silos.

The time wall yield locus was determined for the EAF dusts E and F. The wall friction angle increased the first three day of storage under stress. Up to seven days no more increase of the wall friction angle was observed. Time consolidation resulted in an increase of the wall friction angle of 2° and 3,5° for EAF dust E and F, respectively.

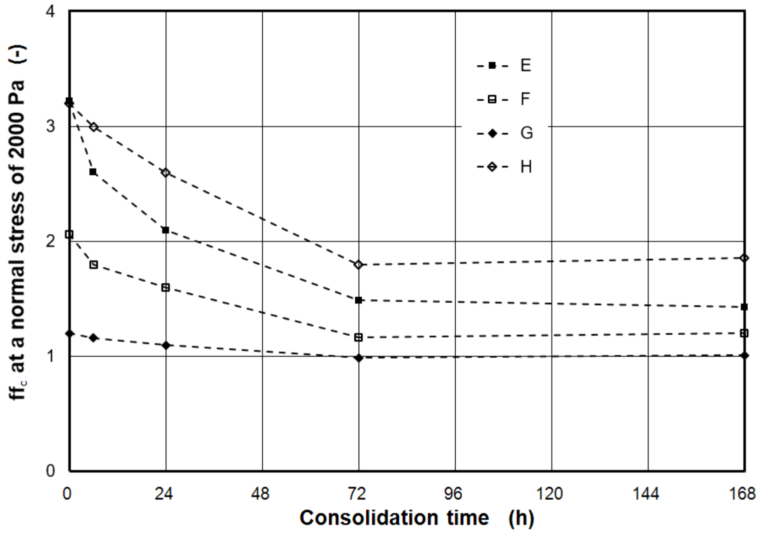

Figure 4 Flowability ff_c of various EAF dusts at a normal stress of 2000 Pa as a function of the consolidation time

4. CONCLUSION

According to the flowability ff_c the flow properties of EAF dusts are in the range “cohesive” to “very cohesive”. The use of the angle of repose for estimation of the flow of EAF dusts is not recommended because of agglomeration effects, which overestimate flow properties. After a storage time of three days all EAF dusts were “very cohesive” because of time consolidation.

Because of the high values of the wall friction angles hopper slope angles in the range of 8° to 17° would be required to obtain mass flow in the hoppers. The recommended safety margin of 2° is considered in these results. Such steep hopper cones are not usual. Therefore, in EAF dust silos and filter hoppers funnel flow has to be expected in most cases.

In silo design, especially in static calculations, the stress dependence of the bulk density has to be considered, since the average real bulk density can be considerably higher than the bulk density according to standard measuring methods.

For investigations on time consolidation of EAF dust a testing period of three days seems to be sufficient since after this period no more change in flowability and wall friction angle was observed.

ACKNOWLEDGEMENTS

The study was financially supported by K1-MET. K1-MET is a member of COMET – Competence Centers for Excellent Technologies and is financially supported by the BMVIT (Federal Ministry for Transport, Innovation and Technology), BMWFJ (Federal Ministry of Economy, Family and Youth), the federal states of Upper Austria, Styria and Tyrol, SFG and Tiroler Zukunftsstiftung. COMET is managed by FFG (Austrian research promotion agency). Laboratory work by R. Oberhamberger and A. Al-Farsi is gratefully acknowledged.

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