PROPERTIES OF STEELMAKING DUSTS FROM DRY DUST SEPARATORS

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Abstract

During the production of plain carbon steel from hot metal and/or scrap considerable amounts of dust-laden off-gases are produced. In de-dusting of these off-gases considerable amounts of fine grained residues are produced, which have to be stored, transported and handled. Thereby, the flow-related properties of the dusts are of great importance. In this study the mechanical properties of dusts from dry off-gas de-dusting in steelmaking plants were investigated. The mass median diameters of electric arc furnace (EAF) dust, basic oxygen furnace (BOF) primary de-dusting dust and vacuum degassing dust (VD) were in the range of a few micrometer, while it was up to more than 100 µm for the residues from the pre-separators in EAF and BOF de-dusting. The values for the particle density were quite similar for all dusts (approximately 3,800-4,800 kg/m³), but the bulk density of the dusts varied in a wide range (approximately 190-1,900 kg/m³). With respect to the flow relevant parameters - flowability, angle of internal friction, wall friction angle and angle of repose - the investigated dusts can be split into two groups: the coarse residues from the pre-separators, which are characterized by low values for the angles and a good flowability, and all other dusts with higher values for the angles and a flowability in the range of very cohesive to cohesive.

Keywords: Steelmaking dust, BOF dust, EAF dust, dust flowability, dust properties

1. INTRODUCTION

During the production of plain carbon steel from hot metal and/or scrap considerable amounts of dust-laden off-gases are produced. The off-gas from electric arc furnaces (EAFs) is usually cleaned in dry de-dusting systems, while the off-gas from basic oxygen furnaces (BOFs) is mainly de-dusted by means of scrubbers. However, in some steel mills dry electrostatic precipitators (ESPs) are used for BOF off-gas de-dusting [1].

In the BOF process the BOF gas is generated during oxygen blowing. In most steel plants suppressed combustion is applied and the BOF gas is recovered as a fuel. The BOF gas is loaded with a large amount of dust. During blowing most of the dust released from the converter is evacuated by the primary ventilation and de-dusting system. Dry primary de-dusting is performed in two stages. The spray cooler, installed to keep the gas inlet temperature of the BOF gas at the ESP inlet below the limit temperature, also acts as a deflector and separates the coarse dust. Subsequently, the fine dust is separated in the ESP. A secondary ventilation and de-dusting system is usually installed to abate the dust emissions not captured by the primary ventilation system. This system usually consists of a canopy hood just above the converter in the tilted position and a doghouse around the remaining area of the converter. The treatment of the evacuated gases is usually performed by means of an ESP or a fabric filter. During charging or tapping operations, the converter is tilted. Thus, the dust emitted in these periods is extracted mostly by the secondary ventilation system. Some other dust emitting process steps, e.g. hot metal desulphurization, tapping operations, handling of additives and continuous casting, are also connected with the secondary ventilation system. The amount of dust collected is in the range of 12-23 kg/t LS (liquid steel) and 0.1-1.2 kg/t LS for the primary and the secondary de-dusting system, respectively [1].

In the EAF process approximately 85-90 % of the total emissions during a complete tap-to-tap cycle are contained in the primary off-gas, which is extracted from the furnace via a hole in the furnace roof. As off-gas treatment usually requires a lot of space it is performed at some distance from the furnace. Only the coarsest fraction of the dust is separated in the so-called drop-out-box situated near the furnace to avoid extensive sedimentation of dust in the off-gas ducts. Before de-dusting, usually the off-gas is treated in a post combustion chamber and, subsequently, cooled e.g. in a quench or a forced draught cooler. Secondary emissions generated during scrap handling, charging and tapping, as well as those escaping from the furnace openings such as fumes, are captured by a canopy hood generally located above the furnace. The secondary emissions may contain the same pollutants contained in the primary emissions. Therefore, both off-gas flows are de-dusted in the same device, mostly by fabric filters [2-4]. Emissions from secondary metallurgy, collected by canopy hoods and roof extractions, are also de-dusted in the same system. The amount of EAF dust collected is in the range of 20-30 kg/t LS [1]. The off-gas from vacuum degassing (VD) units is de-dusted in separate filters installed upstream of the vacuum pumps [5].

The chemical composition of dusts from EAF plants has been investigated frequently [1,6-10] and also chemical analysis of BOF dust is available [1,2]. In contrast, data of the physical properties of such dusts are very rare in relevant literature. For EAF dust a bulk density of 0.96 kg/dm³ and a particle density of 5.25 kg/dm³ were reported [11]. In another study the density was in the range of 2.96 - 4.12 kg/dm³ [9]. The particle size distribution of EAF dust has been presented in a few studies, [6-8,12] and in a further study the mass median diameters of various EAF dusts were reported [9]. For the mass median diameter of BOF dust a value was reported [13].

In a corresponding literature search no data were found with respect to flow properties of dust from steelmaking plants. However, these properties are quite important for dust handling and storage as well as for further treatment and utilization of the residues. The dusts collected are bulk materials which have to be discharged safely from the hoppers of the dust separators and then conveyed and stored in silos. Finally, the residues have to be utilized in other processes directly or after some pre-treatment. Physical properties of the dust, like the bulk density, the angle of repose and the flow properties are relevant for the design of dust conveyors, storage facilities and treatment processes [14,15].

For this study, various dusts from dry de-dusting systems in steelmaking plants were collected. From these residues the particle size distribution, the densities and the flowability-relevant properties were determined.

2. MATERIALS AND METHODS

2.1. Materials

The dust samples A, B and C were collected from the fabric filters of the de-dusting systems of EAF plants. The dust sample D was collected from the drop out box and dust sample E was collected from the bottom discharge of the evaporative cooler upstream of the filter where dust sample C was collected. The dust samples J and K were collected from the ESP of a BOF dry primary de-dusting system. Dust sample L was collected from the bottom discharge of the evaporative cooler upstream of the ESP where dust sample K was collected. The dust samples M and N are from two secondary de-dusting fabric filters of converter steel shops. The dust samples P and Q were collected from the de-dusting filter of a VD unit.

Approximately 1-2 dm³ of each dust sample were taken from the dust discharge of the respective de-dusting units. The volume of the dust samples was reduced to a volume suitable for the various laboratory tests using sample dividers (Haver RT 12.5, Quantachrome Micro Riffler) which were applied repeatedly.

2.2. Measurement of physical properties

The moisture content of the dust samples was measured gravimetrically using a Sartorius MA35M infrared moisture analyser. The dust samples were dried at 105 °C until constant weight was reached.

The particle size distribution of the dust samples was measured using a Sympatec HELOS/RODOS laser diffraction instrument with dry sample dispersion. The particle size distribution of the coarse dust samples was determined using a Fritsch ANALYSETTE 3 PRO laboratory sieve shaker with sieves from 1.0 mm to 500 µm. The undersize material (< 500 µm) was analyzed using the laser diffraction instrument. The mass median diameters d_{50} of the particle size distributions were calculated by linear interpolation between the two measured values next to it. The d_{50} is the particle size with 50 % of the mass of the material consisting of particles smaller than this size and the remaining material consisting of larger particles.

The particle density ρ_P was determined according to EN ISO 8130-3. This method is based on determination of the mass and the volume of a test portion using a liquid displacement pyknometer. The capacity of the pyknometer used was approximately 105 cm^3 and n-heptane (density: 0.681 g/cm^3) was used for displacement of the air. The bulk density ρ_B of the dust samples was measured according to EN ISO 60. The bottom cover of a funnel is removed to discharge 120 cm^3 of dust stored in the funnel. The dust flows by gravity into a coaxial 100 cm^3 measuring cylinder. The excess material is removed by drawing a straight blade across the top of the cylinder.

The porosity (voidage) ε of a dust can be calculated from the density and the bulk density as $\varepsilon = 1- \rho_B/\rho_P$.

The angle of repose of the dust samples was determined according to ISO 4324. The dust flows out of a special funnel placed at a fixed height above a flat and level circular plate. The base angle of the material cone obtained is calculated from the diameter of the base plate and the height of the cone.

2.3. Shear tests

The yield locus for the dust samples was determined using a Schulze RST-XS ring shear tester with a 30 cm^3 shear cell. Each point of a yield locus is obtained in two steps. In the pre-shear step, the sample is consolidated and the point of steady-state flow is determined consisting of a pair of values for the normal stress σ and the shear stress τ. In the second step, a point of the yield limit is determined 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 this procedure. The bulk density of the dust sample is calculated from the measured height of the sample in the shear cell and its mass. A Mohr stress circle, tangential to the yield locus and running through the point of steady-state flow, can 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 [14]. The test procedure was conducted at four different values of the normal stress (600 Pa, 2,000 Pa, 6,000 Pa and 20,000 Pa).

The wall yield locus for the dust samples was determined using a wall shear cell. The bottom ring of this shear cell is formed by a sample of the wall material which was structural steel S235JR. The dust sample in the shear cell is loaded vertically at a normal stress level and then moved relative to the wall material surface at a constant rotation velocity. The points of a wall yield locus resulting from corresponding pairs of values for the normal stress and the shear stress are determined. The slope of a straight line running through the origin of the σ-τ-diagram and a point of the wall yield locus is the kinematic angle of wall friction [14].

A quantitative characterization of the flow properties of a dust can be given by the flowability ff_c, which is the ratio of the consolidation stress σ_1 to the unconfined yield strength σ_c [16]. The larger the ff_c is, the better a granular material flows. The consolidation stress is equal to the major principal stress of the Mohr stress circle which is tangential to the yield locus and runs through the point of steady-state flow. The unconfined yield strength results from the stress circle which is tangential to the yield locus and runs through the origin [15]. The usual classification used to define flow behaviour consists of five categories: 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: $10 < ff_c$ [16]. The flowability of a granular material often depends on the consolidation stress. This can be visualized best in a diagram showing the unconfined yield strength dependent upon the consolidation stress when the diagram also includes lines of constant ff_c [16]. Logarithmically scaled axes improve the representation of the results in the diagram [17].

3. RESULTS

3.1. Particle size

The particle size distributions of the dusts are shown in **Figure 1**. The particle size of the dusts collected from BOF primary de-dusting ESPs (dust J and K) is very fine. The mass median diameters were 1.4-1.5 µm (**Table 1**) and the maximum particle size was approximately 20 µm. These values are slightly less than the reported mass median diameter of BOF dust separated by a dry ESP of 3.2 µm [13]. The bimodal shape of the particle size distribution with a modus in the range of approximately 1 µm, and another in the range of approximately 10 µm, is similar. The particle size distribution of the dusts A, B and C from the EAF de-dusting filters is quite similar to the size distribution of BOF dust. However, besides the majority of the dust which is in the same size range as the BOF dust, there is also a certain fraction of the dust ranging in size between 20-80 µm. Most literature data are similar: reported mass median diameters are in the range of 0.5-1.88 µm [5-7] and maximum particle size 50-100 µm [5,6]. However, there is also an EAF dust reported with a mass median diameter of 19.3 µm and a maximum particle size of 500 µm [12]. A possible explanation for such a coarse EAF dust could be due to no pre-dedusting or poor dust separation in the pre-dedusting step.

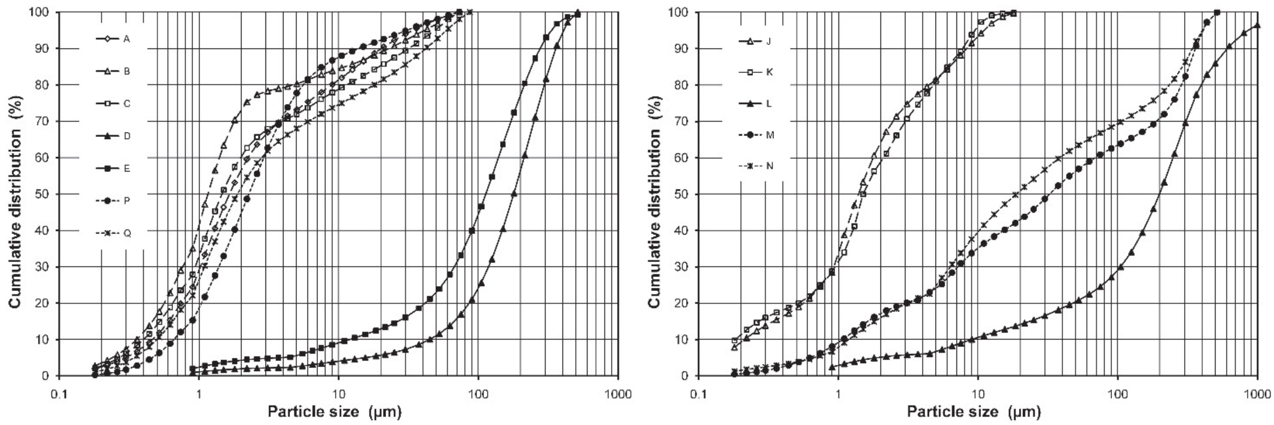

Figure 1 Particle size distribution of EAF steelmaking dust (left) and BOF steelmaking dust (right)

The residues from the pre-separation steps were considerably coarser, both for the BOF and the EAF de-dusting systems. The mass median diameters were in the range of 100-200 µm. For the dusts D and E from the VD de-dusting systems a similar particle size distribution was measured as for the EAF dusts, but there was a higher variation in the size distributions.

3.2. Densities and angle of repose

The values of the particle density were quite high for all dusts (**Table 1**). This results from the high iron content of steelmaking dusts. The density of the dusts from BOF steelmaking (3,850-4,800 kg/m³) was somewhat higher than the density of the dusts from EAF steelmaking (3,780-4,030 kg/m³). The average density for the EAF dusts was 3,900 kg/m³, which is in the upper range of the values reported in [9]. The bulk density of the coarse dusts from the pre-separators (D, E, L) was in the range from 1,560 kg/m³ to 1,880 kg/m³. Thus, the porosity was in the range of 0.53-0.64. For the dusts from the EAF de-dusting filters (A, B, C) and from BOF primary de-dusting ESPs (J, K) the bulk density varied from 590 kg/m³ to 950 kg/m³. The finer the dust was, the lower was the bulk density. The range of the calculated porosity was 0.75-0.84. The bulk density of the dusts from BOF secondary de-dusting (M, N) lay within the same range, although the particle size of these dusts was coarser. For the two dusts from VD de-dusting (P, Q), the difference in the bulk density was surprisingly high because the difference in particle density and particle size was slight.

Table 1 Dust properties

Dust sample	Moisture content (%)	Bulk density* (kg/m³)	Density (kg/m³)	Mass median* diameter (µm)	Relative span $(d_{90}-d_{10})/d_{50}$	Porosity	Angle of repose (°)
EAF plants							
A	0.5	950	3,880	1.7	12	0.76	43
B	0.6	590	3,780	1.2	20	0.84	46
C	0.6	810	4,030	1.5	32	0.80	49
D	0.1	1,880	3,990	179	1.8	0.53	37
E	0.2	1,560	3,980	113	2.4	0.61	37
BOF plants							
J	0.2	760	4,790	1.4	5.8	0.84	48
K	0.3	650	4,610	1.5	5,0	0.86	51
L	0.1	1,730	4,800	199	2.1	0.64	39
M	1.3	610	3,850	32.7	11	0.84	52
N	1.6	750	4,010	18.8	18	0.81	51
VD units							
P	3.0	190	3,680	2.3	5.8	0.95	43
Q	0.4	610	4,390	1.9	22	0.85	44

* Data are already available in another study [26]

Figure 2 shows the bulk density of the various dusts as a function of the consolidation stress measured in the shear tests.

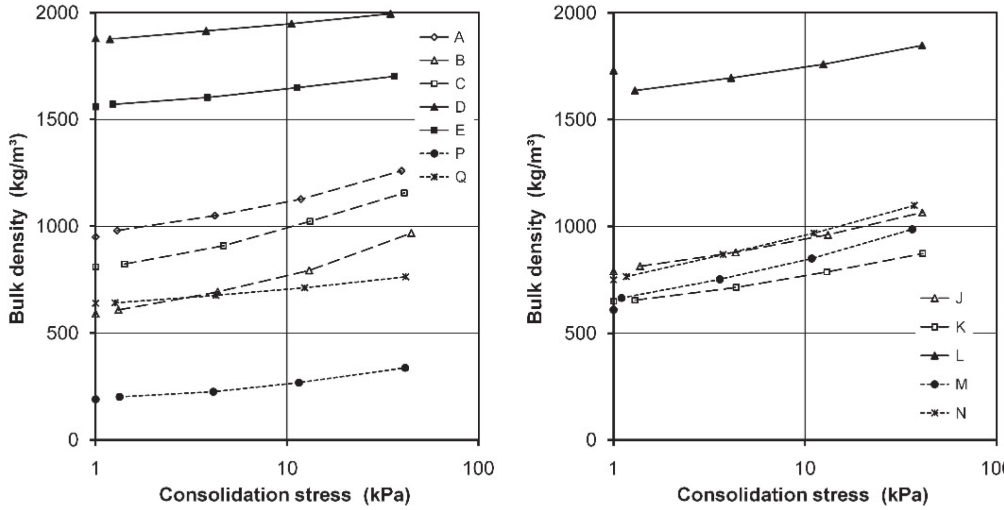

Figure 2 Density as a function of the consolidation stress of the residues from steelmaking de-dusting: EAF steelmaking (left) and BOF steelmaking (right)

The density of the dust samples increased with increasing consolidation stress. The dependence of the bulk density on the consolidation stress can be approximated by equations of the type $\rho_B = B \cdot \sigma_1^c$. All correlation coefficients for these approximations were higher than 0.99. The values for the bulk density measured according to EN ISO 60 at a consolidation stress of 1.0 kPa are shown in **Figure 2**. For most dusts these values correspond quite well with the density curves. A similar behaviour was reported also for dry gas-cleaning dusts from sinter plants and blast furnaces [18,19].

The angles of repose were lowest for the coarse dust from the pre-separators (**Table 1**). For both dust types from BOF de-dusting (J, K, M, N) the highest angles of repose were measured. For the EAF dusts (A, B, C) and the VD dusts (P, Q) the angles of repose were smaller, although these dusts have a similar size to the ESP dusts from the BOFs. This behaviour could be explained by the small agglomerates formed by this dust. Such an effect was also observed for the fine dust from sinter plants [18,20].

3.3. Effective angle of internal friction and wall friction angle

In **Figure 3** the effective angles of internal friction are shown for all dust samples as a function of the concolidation stress. Generally, the effective angles of internal friction are not strongly dependent on the consolidation stress. The highest values for the angle of internal friction were found for the EAF dusts (A, B,C) and for the BOF primary de-dusting dusts (J, K). In **Figure 4** the wall friction angles are depicted as a function of the wall normal stress. For the wall friction angles of the coarse residues from the pre-dedusting units (D, E, L) a significant decrease of the wall friction angle with increasing wall normal stress was observed. This effect was far less noticeable for the the EAF dust (A, B, C) and the ESP dust from BOF de-dusting (J, K). For the dusts from VD units (P, Q) and from BOF secondary de-dusting (M, N), even a slight increase of the wall friction angles with increasing wall normal stress could be preceived.

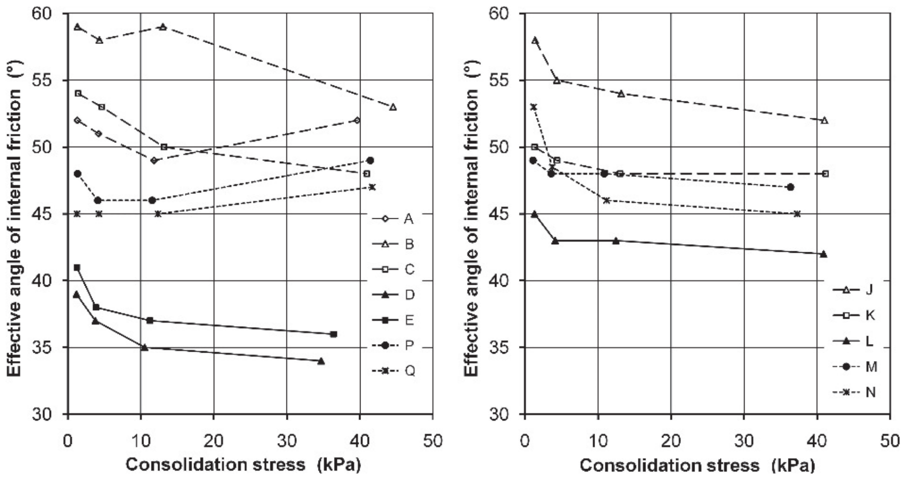

Figure 3 Effective angle of internal friction of EAF steelmaking dust (left) and BOF steelmaking dust (right)

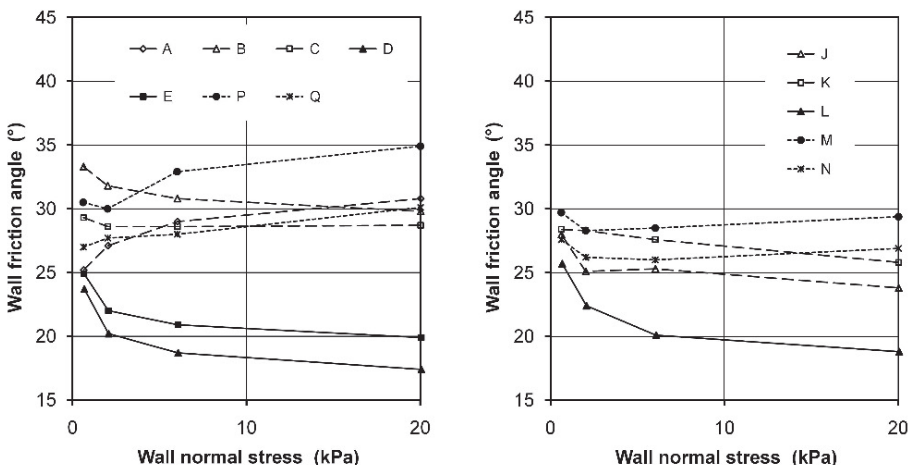

Figure 4 Wall friction angles of EAF steelmaking dust (left) and BOF steelmaking dust (right)

3.4. Flowability

The results for the flowability are presented in **Figure 5**. Generally, the flowability was good for the coarse dusts from the pre-separators. The residues from the EAF de-dusting pre-separators (D, E) were in the flow category free-flowing, while the residue from the BOF primary de-dusting pre-separator (L) was easy-flowing. The BOF dust from primary (J, K) and secondary (M, N) de-dusting showed a similar flowability, although the secondary de-dusting dusts were considerably coarser. The flowability category was very cohesive to cohesive for both dust types.

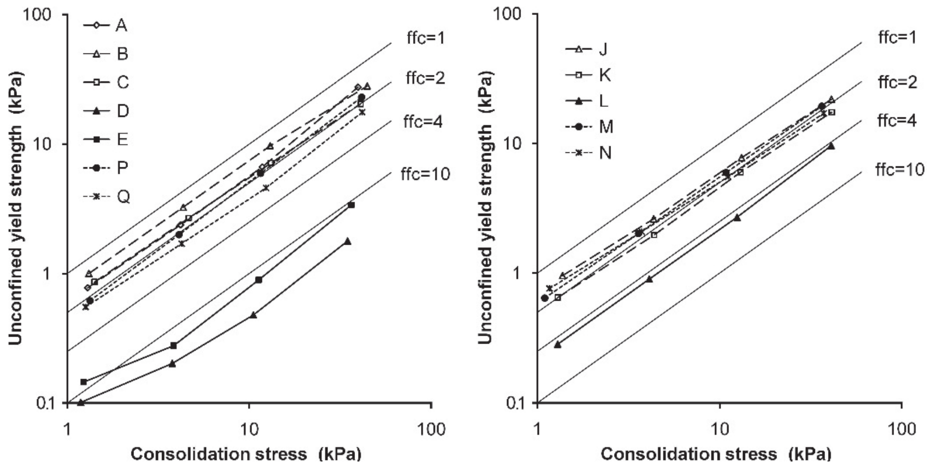

Figure 5 Flowability of EAF steelmaking dust (left) and BOF steelmaking dust (right)

4. CONCLUSION

Various steelmaking dusts from dry off-gas de-dusting systems were investigated in this study with respect to mechanical and flow properties. The results showed that the particle size of the dusts from the EAF and BOF steelmaking are of similar size. This was found for the residues from the pre-separators as well as for the filter dust from EAF off-gas cleaning and also for the ESP dust from BOF primary de-dusting. The mass median diameters of the residues from the pre-separators were in the range of 100-200 µm, while the mass median diameters of the filter and ESP dusts were in the range of 1-2 µm. The dusts from VD units lay in the same size range. The mass median diameters of the dusts from BOF secondary de-dusting were approximately 20-30 µm.

The particle density was high for all dusts which can be explained by the high iron content of steelmaking dusts. In contrast, the bulk density varied in a wide range. With the exception of one VD dust with the extreme low bulk density of 190 kg/m³, the bulk density was in the range of 590-1,880 kg/m³. The high values for the bulk density (>1,500 kg/m³) were found for the coarse residues from the pre-separators.

The flowability expressed as ff_c was best for the coarse residues from the pre-separators. The flowability was quite independent from the consolidation stress. For the other dusts the flowability improved slightly at higher values of the consolidation stress, but no distinct relationship between size and flowability was established.

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