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Iron Ore Pellet Dustiness Part I: Factors Affecting Dust Generation

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Iron ore pellets abrade during handling and produce dust. This study was conducted to determine what factors affect pellet dustiness, and whether dustiness can be related to the abrasion index. Factors studied included bed depth within a straight grate furnace; pellet chemistry; firing temperature; coke breeze addition; and tumble index. Abrasion indices for all pellet samples ranged from 1.9–5.0% (20 samples) and from 7.1–27.5% (5 samples). Pellets were dropped in an enclosed tower, which enabled the collection of airborne particles generated during pellet breakdown. The quantity of airborne particles generated by each pellet type was 10–100 mg/kg-drop, or 50–500 mg/kg over five drops through the tower. Pellet dustiness was predominantly affected by pellet chemistry and by pellet firing temperature. Results showed a nearly 21% increase in dustiness for every percent decrease in firing temperature – this was based on a typical firing temperature of 1280°C. Pellet dustiness was regressed to the pellet abrasion index (for AI < 5%), which yielded a correlation coefficient of 0.22. These results show that, although AI is one of the best indicators of fired pellet quality and can indicate high levels of dust, it could not explain the dustiness of good quality pellets.

The second paper (Iron Ore Pellet Dustiness Part II) explains the relationship between AI and dust for good-quality pellets; and compares fines generation between pellets fired in Straight-Grate (Traveling Grate) and Grate-Kiln furnaces.

Keywords: abrasion, agglomeration, dust, dustiness, iron ore pellets, pelletization

Introduction

Researchers have investigated many topics of importance to the iron ore industry. Recently published topics include flotation reagents and chemistry (Sandvik and Larsen2014; Manouchehri 2014), filtration (Carlson and Kawatra2008; Haselhuhn et al. 2012b), water chemistry and zeta potential (Westerstrand and Ohlander 2012; Carlson and Kawatra 2008; 2011; 2013; Haselhuhn 2012; 2013; Haselhuhn et al. 2012a), and agglomeration (Halt et al. 2014; Kawatra and Halt 2011). However, very little research exists regarding the problem of dust generation from pellets. Dust generation should be understood in order to improve emission control and minimize waste generation.

Bulk granular materials (i.e., coal, iron ore lump and pellets, limestone, and fertilizer) can fracture and abrade during handling and transportation. The degradation process generates particulate fragments across a wide range of sizes. Certain particle sizes are able to become airborne and are undesired for many reasons. Commonly cited are health and industrial problems associated with various size ranges of emitted particles and their concentrations.

Outside of processing plants, dust and particulate matter emissions are commonly combated by spraying copious amounts of water and/or applying various types of chemical reagents to storage piles and material transfer points. The chemicals bind particles together, increase particle wetting, and water retention and can effectively reduce dust (Copeland and Kawatra 2005); although, they must be repeatedly added and do little to limit the generation of fine particles. Inside of the plants, material flows are contained, and process gases cleaned via wet scrubbers, bag houses, or electrostatic precipitators (Bolen2014), before they are emitted to the environment. All of the above approaches only serve to collect, capture, or suppress fine particulates that have already been generated.

Alternatively, one could ask whether the generation of finely sized particles can be reduced. In other words, what controls the generation of potential dust particles when handling pellets? Do changes in processing conditions alter quantities of dust generated during handling? Do certain processing conditions lead to higher levels of dustiness? Can the knowledge of dust generation be used to better predict appropriate levels of chemical reagents required for dust suppression and when dust suppression will be needed?

The purpose of this paper is to determine whether the abrasion index can be related to pellet dustiness. Direct measurements of airborne mass, generated by handling
various types of pellets in a drop tower, are compared to pellet abrasion indices. Iron ore pellets were of considerable regional interest, as approximately 50 Mt of pellets are produced and shipped per year in the Great Lakes region of the upper Midwest, USA.

Theoretical Background

Iron Ore Agglomeration

The prevalence of high-grade ores is declining worldwide, so low-grade iron ores are processed more frequently (Liu et al. 2014). After processing, the concentrates are agglomerated into pellets. Pellets enable beneficiated low-grade iron ores to be used in blast furnaces and direct reduction shaft furnaces. During agglomeration, moist, finely sized, iron-rich powder, powdered flux materials such as limestone, dolomite, and olivine (Semberg et al. 2014) and binders (Halt and Kawatra 2014) are rolled into spherical balls, and subsequently heat hardened into pellets. Factors affecting pellet dustiness can range from inputs to agglomeration; to induration or heat hardening conditions; to the type and extent of handling – all may interact to some degree to affect final pellet structure and properties and ultimately dust generation (Figure 1).

Abrasion Resistance of Iron Ore Pellets

Abrasive wear of granular materials tends to produce fine particles with little change in the original granule size distribution (Pierce et al. 1980; Werther and Reppenhagen 1998). The fine particles from abrasion then contribute to dust while handling pellets. Consequently, the purpose of this paper was to investigate whether (a) variables that alter pellet quality and abrasion indices also affect their dustiness; and (b) the Abrasion Index can be used to empirically test pellet dustiness.

Standardized tests are used to report the abrasion resistance of pellets. The Abrasion Index, or AI, reports the percent of material smaller than 600 μm (ISO 3271:2007) generated during a tumble test. A higher AI signifies weaker pellets that degrade more easily and produce more fines. Maximum limits on AI vary with pellet consumer, but are generally desired to be less than five percent using the ISO tumble test (Geerdes et al. 2009).

It is well known that additives such as bentonite clay and calcium hydroxide can lower the abrasion index of iron ore pellets; increasing the ore’s specific surface area can lower abrasion indices as well (Meyer 1980). Others have shown that iron ore pellets from different pelletizing plants generated varying quantities of fine particles (<600 μm) using a set of mechanically agitated screens (Copeland and Kawatra 2005). The controlling factor was speculated to be differing types of furnaces used to heat-harden the pellets. It is generally accepted that pellets indurated in Straight-Grate and Rotary Kiln furnaces produce different quantities of before-tumble fines (Oja 2013). This is due to differences in firing uniformity between the two types of furnaces. Additionally, the tumbling action in rotary kilns may remove particles weakly attached to the agglomerate structure.

Common Definitions of Dust

Two relevant particulate size ranges commonly accepted as dust include Total Suspended Particulates and PM₁₀. These particle size ranges are defined using the aerodynamic diameter.

- **Aerodynamic diameter**: The aerodynamic diameter is used to classify particles according to their settling behavior in air (Baron and Willeke 2001). Imagine dispersing a handful of a dry, non-homogeneous powder into still air and analyzing particles as they settle to the ground. At every instant in time, the particles collected will span ranges of size, density, and shape. All particles that settle at the same rate and are collected at the same instant in time can be classified with an equivalent aerodynamic diameter.

The aerodynamic diameter is defined as the size of an idealized spherical particle with a density of 1000 kg/m³ with equivalent settling behavior as the particle of interest (Baron and Willeke 2001; EPA 2013). Simply put, particles with identical aerodynamic behavior can be physically quite different. In general, aerodynamic diameter decreases with particle size, and increases with density and as particles become less spherical. Figure 2 is a plot of calculated aerodynamic diameter (μm) as a function of particle density (kg/m³) and diameter (μm).

Figure 2 illustrates two general principles. At constant particle density, aerodynamic diameter increases with increasing particle diameter. At constant particle diameter, aerodynamic diameter increases with increasing particle density.

- **Total suspended particulates**: Total suspended particulates, or TSP, includes all dust particles suspended in air that are captured and reported by the sampler. Generally, dust has been considered to be particles with diameters less than 75–100 μm (ISO 4225:1994; IUPAC 1990). Historical particulate matter regulations set limits on TSP emissions.

  - **PM₁₀**: PM₁₀ consists of particulate matter with an aerodynamic diameter of 10 μm or smaller. PM₁₀ may be called coarse, inhalable particles (EPA 2013).
Materials and Experimental Methods

Materials

Twenty-five types of iron ore pellets were received for dustiness testing. Some samples were made by industrial iron ore pellet plant operations; other samples were made in a laboratory following accepted agglomeration and firing procedures. The pellets were classified into certain groups for comparison, as shown in Table 1. A brief description of each group of pellets is as follows:

**Bed level:** The “Bed level” pellets were industrial pellet samples. These samples were collected from different depths in a bed of pellets fired in a Straight-Grate furnace.

**Pellet chemistry:** The “Pellet chemistry” pellets were industrial pellet samples. These samples represent a wide range of chemical and mineralogical contents, as they were prepared using a variety of ores, binders, and levels of flux. Samples were collected from industrial pelletizing plants, so unavoidable differences in firing conditions may have been present for each sample.

**Firing temperature:** The “Firing temperature” pellets were laboratory pellet samples. These samples were fired at three temperatures to determine its effects on pellet dustiness.

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**Table 1.** Iron ore pellet sample description. Industrial pellet samples were supplied by industrial pellet plants. Laboratory pellet samples were made at COREM. “TI” indicates Tumble Index, “HME” indicates heat of magnetite equivalent, and represents the quantity of coke breeze added to green-balls. “Adj. fire” indicates an adjustment to the pot-grate firing procedure. A mini-tumble test was conducted on some samples when too few pellets were available for the ISO procedure.

<table>
<thead>
<tr>
<th>Pellet variable evaluated</th>
<th>Sample name</th>
<th>Notes</th>
<th>Fired compression (kgf)</th>
<th>Tumble ISO (%)</th>
<th>Mini-tumble (%)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>+6.3 mm</td>
<td>−0.5 mm</td>
<td>+6.3 mm</td>
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<td>Bed level</td>
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<td>Middle samples</td>
<td>353</td>
<td>97.1</td>
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<td></td>
<td>Bottom samples</td>
<td>302</td>
<td>96.8</td>
<td>3.1</td>
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<td></td>
<td>Hearth samples</td>
<td>294</td>
<td>96.3</td>
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<td></td>
<td>Plant A Industrial pellet</td>
<td>178</td>
<td>90.9</td>
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<td>Pellet chemistry</td>
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<td>97.0</td>
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<td>Plant E samples</td>
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<td>97.5</td>
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<td>Plant F samples</td>
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<td>Plant G samples</td>
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<td>Firing Temperature</td>
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<td>72.5</td>
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<td>1200°C samples</td>
<td>164</td>
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<td>1280°C samples</td>
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<td>Excess coke</td>
<td>80% HME Laboratory pellet</td>
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<td>97</td>
<td>2.9</td>
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<td></td>
<td>90% HME samples</td>
<td>272</td>
<td>96.3</td>
<td>3.5</td>
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<tr>
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<td>90% + adj. fire samples</td>
<td>310</td>
<td>96.7</td>
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<td>366</td>
<td>97.2</td>
<td>2.7</td>
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<td>107% HME samples</td>
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<td>97</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>107% + adj. fire samples</td>
<td>230</td>
<td>96.6</td>
<td>3.1</td>
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</table>

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Fig. 2. Calculated aerodynamic diameter, in μm, as a function of particle density, in kg/m³, and diameter, in μm. For these calculations, particles were assumed to be spherical with a shape factor of 1.

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Excess coke: The “Excess coke” pellets were laboratory pellet samples. These samples were prepared from a hematitic ore and various levels of coke breeze as an internal fuel source. Pellets were made at two basicities. Coke levels are reported as percent HME, or Heat of Magnetite Equivalent. Higher HME is provided by higher levels of coke breeze in the green-balls (unfired pellets).

Tumble Index: The “Tumble Index” pellets were industrial pellet samples. Two chemistries were provided, each with a “good” and “bad” Tumble Index as indicated by the industrial pellet plant.

Dust Tower Description

The dust tower used in this study was originally designed to test the effectiveness of dust suppressants for iron ore pellets (Copeland and Kawatra 2011). The height (2.7 m) was chosen to be representative of typical drop heights at iron ore handling facilities in the Great Lakes region of the upper Midwest, USA. Material dropped through the tower collides with several impact plates; kinetic energy from the fall is dissipated by elastic material deformation, friction during rolling and sliding, and by particle breakage. As the forces seen by each particle are held constant (assuming constant particle mass), the type and extent of particle breakage depends on the material properties and processing history of the handled material. A schematic of the dust tower is shown in Figure 3.

As material falls through the tower, a vacuum system pulls air up through the tower at approximately 8 l/s, entrains certain sized particles produced within the tower, and carries them to a filter paper (Whatman 113, 30 μm pore diameter) in the vacuum system line where they are collected for analysis. Based on channel dimensions in the dust tower, a volumetric flow rate of 8 l/s corresponds to a 0.6 m/s vertical air velocity. PM_{10} mass concentrations can be measured by an aerosol monitor that samples dust-laden air prior to the particulate filter.

Effects of Experimental Parameters on Cumulative Mass Measurements

Preliminary experiments were conducted to determine effects of dust tower variables on the cumulative mass of airborne particles collected. Variables tested were sample quantity (0.4, 1.0, and 1.7 kg); number of drops (1–5); and sample pre-cleaning (as-received, blown off with compressed air). All samples were dried (150°C) and screened (+¼ in./6.4 mm) before dropping through the tower. Pellet samples used for preliminary experiments were Pellet chemistry – Plant E, as a large supply was readily available.

Preliminary work showed a slight increase in the collected airborne mass when sample quantity increased. Airborne mass increased from 45 to 50 mg/kg-drop at drop 1 when sample quantity increased from 0.4 to 1.7 kg. Mass per drop decreased during drops 2–5, and stabilized around 25–30 mg/kg-drop. The minimal increase in airborne mass for larger sample quantities suggested pellet-pellet interaction was not a significant contributor of fine particles during dust tower testing. It had been expected that dropping increased quantities of pellets through the tower would increase airborne mass due to additional abrasive “events” between pellets. It appeared that fine particles were produced by pellet surface degradation only during interactions with the impact plates.

Additional tests conducted at constant sample size (1 kg) and varying pellet diameters resulted in a direct correlation between change in surface area and change in airborne mass collected. Decreases in particle diameter led to larger cumulative airborne mass measurements. Particulate matter generation occurred by abrasion in the dust tower.

Pellets, dried at 150°C and screened to +1/4 in./6.4 mm, were tested as-received and after a “cleaning” procedure. During cleaning, dried, pre-screened pellets were blown with compressed air for 30 s. The cleaning procedure reduced cumulative airborne mass from 60–65 mg/kg to 20–25 mg/kg. Cleaning pellets with compressed air reduced cumulative airborne mass to similar stabilization values as observed after multiple drops using as-received pellets. Taken together,
these observations suggested that handling prior to and during sample preparation was an important contributor to dust formation and its effects should be minimized when testing pellets for their propensity to produce dust.

The final procedure used to evaluate the 25 types of pellets in this study included drying (150°C), screening (+1/4 in./6.4 mm), and cleaning with compressed air for 30 s. This resulted in a reproducible measurement of cumulative airborne mass that linearly increased with number of drops through the tower (Figure 4). In the Results section, cumulative airborne mass measurements are reported after 5 drops through the tower.

Results and Discussion

Direct measurements of cumulative airborne mass produced during pellet handling were measured using MTU’s dust tower. Airborne particles were concentrated into a small duct and filtered out of the air stream by a filter paper. Changes in filter paper weight were attributed to airborne particles. Cumulative airborne mass for each pellet type is shown in Figures 5a–f. No trends were observed using the aerosol monitor: deviations in the PM₁₀ measurement were of the same order of magnitude as the measurements.

Effects of Bed Level

In Straight-Grate (or Traveling Grate) furnaces, there is a temperature gradient between pellets at different bed depths. The temperature gradient can lead to variations in pellet physical and metallurgical quality with depth, or level, in the pellet bed. Oja (2013) showed bottom-of-bed pellets had a greater quantity of weak pellets (% −300 lbs) and a lower tumble index (% +6.4 mm) compared to the middle and top layers, while the top-of-bed pellets were brittle (very wide deviation in the percent −6.4 mm material produced by 10–50 ft. drops) compared to the middle and bottom layers. Gudenua et al., (1985) showed that pellet quality deviations due to bed level were pronounced in pellets larger than 10 mm in diameters. They explained that larger pellets in the bottom layer were insufficiently fired, and larger pellets in general require longer induration times.

Here, cumulative airborne mass collected during Bed Level pellet handling ranged insignificantly from 103 to 123 mg/kg (Figure 5a). The pellets from each of the bed layers appeared to be well fired as evidenced by consistent compression strengths (300 kg/pellet) and low abrasion indices around 3% −0.5 mm. The hearth layer pellets had a slightly higher abrasion index (3.7% −0.5 mm) than the other layers; although, this is not currently explained. Hearth layer pellets are recycled through the furnace and undergo a reheating process. Pilot scale studies have shown that repeatedly heating pellets to firing temperatures does not degrade their abrasion index (Martinovic et al. 1998).

Effects of Pellet Firing Temperature

Induration temperature significantly affects pellet quality. Increasing induration temperature is understood to consolidate the pellet structure and reduce porosity. Grains begin necking and bridging and crystal growth occurs, often at a temperature near 1200–1250°C; although, this depends on the ore and additives used.

The firing temperature pellet samples were indurated at three temperatures ranging from a typical firing temperature (1280°C) to a preheat temperature (1050°C). The results showed that cumulative airborne mass decreased linearly with firing temperature (Figure 5f), and there was a linear correlation between AI and cumulative airborne mass for these samples. Overall, the firing temperature results showed a nearly 21% increase in dustiness for every percent decrease in firing temperature – based on the typical firing temperature.
Lowering the firing temperature from 1280°C to 1200°C significantly lowered compression strength (313–164 kg), and increased the Abrasion Index (3.7–11.9%) and cumulative airborne mass (124–289 mg/kg).

These results show that insufficient firing appears to be a major cause for increased generation of fine particles and dust, and there is a critical firing temperature required to achieve good induration. Pellet quality is very sensitive to temperature below the critical temperature. The results also suggest that AI can be used to indicate the propensity for very high levels of dust.

### Comparison Between Cumulative Airborne Mass and Abrasion Index

A major goal of this research project was to determine if iron ore pellet dustiness correlates to abrasion indices, as observed in the three firing temperature samples. The abrasion index is a common pellet quality index used around the world; potentially gleanling more information from a single tumble test would be useful for pellet producers. Figure 6a illustrates what appears to be, at first glance, a strong correlation between cumulative airborne mass and abrasion index ($R^2 = 0.69$) for all samples tested in this study.

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**Fig. 5.** Cumulative airborne mass for each pellet type tested. Pellet samples are (a) bed level; (b) pellet chemistry; (c) excess coke 1; (d) excess coke 2; (e) tumble testing; and (f) firing temperature. Note that a–d y-axes are scaled to 350 while e and f are scaled to 700 mg/kg. Cumulative airborne mass reported after 5 drops through tower. “TI” indicates Tumble Index. “HME” indicates heat of magnetite equivalent, and represents the quantity of coke breeze added to green-balls. “Adj. fire” indicates an adjustment to the pot-grate firing procedure.
The correlation may be explained by effects of incomplete firing on pellet quality, which essentially led to four points on the cumulative airborne mass vs. AI curve (at AI < 5%, 7%, 11%, and 27.5%). Pellets originate from a powder material and will easily degrade back to individual particles and weakly bonded fragments if the induration process and its associated phenomena (oxidation and recrystallization, melt formation, pore size and porosity reduction, and grain growth) are not complete.

The dominant effect of pellet firing on dustiness was supported by only considering pellet types with abrasion indices less than five percent (% < 0.5 mm). This is shown in Figure 6b. In effect, five pellet samples were removed from the analysis (Tumble Test-Plant Y, Pellet Firing 1050 and 1200°C, and Pellet Chemistry-Plant A). Removing those samples resulted in a very weak correlation between cumulative airborne mass and abrasion index, with an $R^2$ value of 0.22. In other words, variations in abrasion index did not explain variations in cumulative airborne mass for good-quality pellets.

Although not quantified, it was thought that the poor correlation between cumulative airborne mass and abrasion index may in part be explained by the nature of the particulate matter produced by each type of pellet during degradation, and by surface roughness effects.

**Visual Examination of Dust Particles**

The cumulative airborne masses from select samples were visualized under SEM. Loose particles that had collected on the top of the filter paper were deposited on conductive tape and placed on an aluminum SEM stub. A small segment (1 cm x 1 cm) of each filter paper was removed and placed on a stub as well. Samples were carbon coated and visualized under SEM. Representative coarse particles, shown in Figure 7a, illustrate the wide range of airborne particles and sizes produced and collected during this study. Considering a typical hematite density of 5000 kg/m$^3$, the cumulative airborne mass measurement may best be considered as Total Suspended Particulates, although some particles were much larger than traditional dust particles. Using measured airflow data in the dust tower, it was calculated that particles up to an aerodynamic diameter of 200 μm (PM200) may be collected and reported in the cumulative airborne mass measurement. The presence of large particles and fragments may tend to dominate this measurement and effectively mask differences in PM10 generation between samples.

In general, particles ranged from smaller than 1.0–200 μm in diameter. The average and maximum size, as well as the particle fracture surfaces, differed between pellet types. Coarse particles appeared to consist of the original ore particles bonded together into an aggregate structure. Figure 7b shows a fragment from a bentonite-bonded pellet, which appears to have sharp conchoidal features, reminiscent of glassy or brittle fracture. Figure 7c shows an airborne particle originating from pellets agglomerated using an organic binder. In this case, the sharp features were absent. The average and maximum diameters of particles from Plants F and C (two measurements from 60 individual particle for each) were measured to be 73 and 190 μm, and 56 and 157 μm, respectively. These results suggest that the abrasion product size distributions vary between pellet types, which is supported by Copeland and Kawatra (2005).

![Fig. 6. Correlation between total cumulative dust (mg/kg) and Abrasion Index (% <0.5 mm). The regression is shown for all data points (a) and only for AI < 5% (b).](image)

![Fig. 7. SEM micrographs of airborne particles collected while handling various types of pellets: (a) Pellet Chemistry-plant E, scale bar 300 μm; (b) Pellet Chemistry-plant F, scale bar 20 μm; and (c) Pellet Chemistry-plant C, scale bar 20 μm.](image)
Potential Effects of Surface Roughness

Total cumulative airborne mass was generally less than 500 mg/kg pellets after 5 drops through the tower. Due to the small quantities of mass collected during each test, it may be argued that dustiness rankings may have been sensitive to surface effects or variations in surface roughness. Surface roughness effects were observed by Sivrikaya and Arol (2013) in a concurrent study using the dust tower. They evaluated the effects of different organic-inorganic binder combinations on iron ore pellet dustiness. In those trials, pellet dustiness increased with visually observed increases in pellet surface roughness. Here, surface roughness was relatively consistent, except for between a few pellet chemistry samples. Even considering this potential complicating factor, pellet firing temperature was shown to be the most important factor affecting pellet dustiness.

Conclusions

With increasing emphasis on reducing particulate emissions and increased levels of governmental regulations, iron ore pellet producers may need to understand dominant factors contributing to iron ore pellet dustiness. This preliminary investigation directly measured cumulative airborne mass produced while handling 25 types of laboratory and industrial iron ore pellets. Major variables evaluated during this study included bed level, pellet chemistry, firing temperature, excess coke additions, and a comparison between “good” and “bad” tumble test pellets (as designated by the pellet supplier). Three major conclusions drawn from this study are as follows:

- Two variables significantly contributed to the dustiness of iron ore pellets: pellet firing temperature and pellet chemistry. Cumulative airborne mass decreased from 587 to 124 mg/kg when firing temperature increased from 1050 to 1280°C. Cumulative airborne mass collected while handling the Pellet Chemistry samples generally ranged from 71–167 mg/kg, with each sample representing a separate industrial pellet plant.
- Cumulative airborne mass correlated to abrasion index when considering all 25 types of pellets tested in this study ($R^2 = 0.69$). The correlation was explained by the dominant effects of underfiring pellets, which essentially led to four points on the cumulative airborne mass vs. AI curve (at AI < 5%, 7%, 11%, and 27.5%). Under-fired pellets are weak and easily degrade during abrasion, producing a fine powder consisting of individual particles and aggregates similar in structure to the original pellet. Only considering pellets with an abrasion index <5% –0.5 mm reduced the correlation coefficient to 0.22.
- Visually, the collected airborne particles appeared to consist of a wide range of shapes and sizes, which depended on the pellet type. The cumulative airborne mass measurement may have been dominated by the presence of large particles, effectively masking potential differences in PM$_{10}$ generation between pellet types.

In summary, this work was conducted in order to determine if pellet dustiness correlates to the abrasion index. While no correlation existed using pellets collected from many sources, one may be present only using pellets from a single pellet plant.

The second paper (Iron Ore Pellet Dustiness Part II) explains the relationship between AI and dust for good-quality pellets; and compares fines generation between pellets fired in Straight-Grate (Traveling Grate) and Grate-Kiln furnaces.

Acknowledgments

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