Size Selective Dustiness and Exposure; Simulated Workplace Comparisons

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A simulated workplace study was conducted to investigate the relation between inhalation exposure and dustiness determined with a rotating drum dustiness tester. Three powders were used in the study, i.e. magnesium stearate, representing a very dusty powder, and aluminium oxide and calcium carbonate, representing low and very low dusty powders, respectively. Two scenarios of handling small volume of powders were included; sweeping/cleaning and scooping/weighing/adding. Size-selective dust exposure was assessed using MultiDust (dual-fraction) IOM and RespiCon® sampling heads. For the present operation scenarios, dustiness showed itself to be the major determinant of exposure and explained ~70% of the exposure variances. The ratios of respirable and inhalable fractions as determined by dustiness tests were comparable with the ratios observed for exposure. The results emphasize the relevance of dustiness as a parameter to characterize substances according to potential for exposure.

Keywords: dust exposure; dustiness; manual powder handling operations; size-selective sampling

INTRODUCTION

Dustiness of dust containing bulk material is defined as the tendency to emit dust into the air during handling under specific conditions (Burdett et al., 2000). The formation and emission of dust during handling depends on the type of handling, size distribution of the bulk material, content of water and other liquids, and several other parameters.

Dustiness tests have been developed and used to characterize product quality of bulk materials, and to predict the potential of powders to pose health risks, safety risks (fire, explosion), environmental pollution or contamination and wear of machinery. No single method of dustiness testing is likely to represent and mimic the various types of processing and handling used in industry. Since dustiness is a relative term and the measurement obtained will depend on the test apparatus and various environmental variables, the need to specify dustiness tests is evident. To provide guidance for reference test methods that classify the dustiness of bulk solid materials in view of workers’ health risk, The European Standardisation Organisation (CEN) technical Committee on Workplace Atmospheres mandated its Working Group 3 to produce such a standard. The results of an EU funded project SMT4-CT96-2074 (Burdett et al., 2000) formed the basis of the first draft of a working document on requirements and test methods to determine dustiness test in terms of health-related fractions. This has been completed recently (CEN, 2004). This draft standard aims to provide specifications for reference test apparatus and reference test methods for the reproducible production of dust under standard conditions, and the measurement of the inhalable, thoracic and respirable fractions of this dust with reference to the existing size fraction definitions, i.e. EN 481 (CEN, 1993).

By defining the relationship between the dustiness determined with a standardized dustiness tester and the dust generation in actual workplace conditions, classification of bulk materials according to their dustiness may be useful for preliminary risk evaluation and may lead to better exposure assessments for non-dusty and dusty powders within the scope of European legislation on new and existing substances (e.g. Directive 93/67/EEC), in the future.

Heitbrink et al. (1989, 1990) were among the first who explored a possible relationship between
dustiness and inhalation exposure in workplace powder handling operations, e.g. bag filling, and dumping. These authors reported significant but inconsistent correlations between dustiness test results and workers exposures. When dustiness test results were used to estimate actual dust exposures of individual workers, the prediction intervals were quite large.

To further explore the relationship between dustiness of bulk materials and inhalation exposure in terms of health-related fractions a semi-experimental study was conducted for two scenarios of manual handling of small amounts of powders.

**MATERIALS AND METHODS**

*Experimental*

A semi-experimental setting of the study was chosen to focus on dustiness of the powders that were handled and to minimize the influence of other determinants of dust exposure, e.g. individual behaviour, environmental conditions such as relative humidity, ventilation, and (process) equipment.

Personal inhalation exposure was measured for two exposure scenarios involving manual handling of small amounts of powders, i.e. ‘cleaning/sweeping’ and ‘transfer’ (scooping/weighing/adding). The two exposure scenarios selected for the experiment are considered to represent situations that are found in practice. To exclude the effect of personal working methods, one person per exposure scenario performed the handling. During six experimental days for each scenario the test subject handled three powders that were classified as dusty (one powder) and non-dusty (two substances), respectively. Each substance was handled in a similar way, i.e. same amount or same duration. The order in which the substances were handled was changed every day.

Scooping/weighing/adding involved scooping the substance with a metal scoop from a plastic bin \((H \times L \times W = 55 \times 37 \times 30 \text{ cm})\) with a plastic inner bag onto a scale and subsequently pouring it into another plastic bin \((H \times L \times W = 55 \times 37 \times 30 \text{ cm})\) with a plastic inner bag. The test subject weighed out \(\sim 1 \text{ kg}\) of substance 43 times. During the first trial, the test subject handled the substance until 30 min had elapsed. The amount of powder was observed and registered by the TNO researcher. When the bin containing the substance at the start was empty the substance was transferred the other way around. A fixed amount of substance (43 kg) was transferred during all other trials. Each day a new batch was used. The bins were positioned on the floor; the scale was positioned on a table.

In preparation for the test subject to perform the sweeping/cleaning scenarios, 300 g of the substance was spread (using a brush and a broom) over the table and \(\sim 500 \text{ g}\) was spread on the floor including under the table and into corners. The test subject was instructed to clean both the table and the floor using a hand-broom, a long-handled broom and a dustpan. First, the table was cleaned by sweeping the powder together into a heap and subsequently brushing the powder with the hand-broom onto the dustpan by holding the dust pan just under the surface of the table. The collected powder was then thrown in a dust bin. After sweeping the table, the floor was cleaned by sweeping the powder with the broom to the middle of the room. The amount of collected powder was then swept onto the dustpan with the hand-broom and thrown into the dust bin in two times. Next, the room was swept again to remove the remaining powder. Again the collected powder was swept onto the dust pan and thrown in the dust bin. The task was performed in 15 min (\(\pm 0.5 \text{ min}\)).

Two rooms were used for the experiment. The surface area of the rooms was \(\sim 12.2 \text{ m}^2\), and the volume \(\sim 30 \text{ m}^3\). In one room (Room 1) a table \((\sim 0.7 \text{ m high})\) was placed with a surface area of \(\sim 3 \text{ m}^2\); in the other room (Room 2) a table \((0.8 \text{ m high})\) was placed with a surface area of \(\sim 0.5 \text{ m}^2\) (the scale was placed on this table). During the experiments the door and windows were kept closed. The air exchange rate was determined with a tracer gas method once every day. The tracer gas [sulphur hexafluoride \((\text{SF}_6)\)] was spread in the room and subsequently the decrease in concentration was monitored with a photoacoustic multigas monitor (type 1302; Brüel & Kjær, Naerum Denmark).

Temperature and relative humidity were registered during the experiments using a Vaisala HMP 31 UT (Helsinki, Finland) probe combined with an ELTEK 1007 data logger (Haslingfield, UK) and averaged over the experimental period.

The study protocol was approved by the Medical Ethics Committee, and the test subjects volunteered to participate in the study. The test subjects were two students (age >20 years) recruited by TNO. Prior to entering the study the test subjects were informed in writing about the objective and methods of the study and an informed consent form was completed by each. Prior to each replicate the test subjects were provided with clean Tyvek® coverall work clothing to prevent contamination from previous activities. In addition, they wore protective gloves and a full-face mask with P3-filter.

*Selection of bulk solid materials*

Experimental powders were selected from a list of 10 substances that were reported to be used frequently in workplaces. Preliminary evaluation of the results of dustiness tests for these substances (Chung and Burdett, 1994; Hjemsted and Schneider, 1996; Burdett et al., 2000), combined with considerations of substance toxicity and conditions for chemical analysis resulted in the selection of magnesium
stearate, aluminium oxide and calcium carbonate to be used in the experiment, representing a range of inhalable dustiness mass fractions. Details on the substance properties as provided by the manufacturers are given below.

The aluminium oxide (Al₂O₃) (CAS 1344-28-1) used was a white powder with an angular-shaped grain. Purity was 99.8%. The powder is generally used as a sandblasting agent.

The calcium carbonate (CaCO₃) (CAS 471-34-1) used was a grey/slightly brownish powder. Purity was 98.7%. According to its specification the average particle size diameter is ~12 µm. Calcium carbonate has many uses, e.g. in construction materials; as a raw material in glass; in the manufacture of paper, paints and dyes, carpeting and other floor coverings; and in the treatment of water and industrial waste. Calcium carbonate is also used to reduce soil acidity in agriculture, in food products and in sugar extraction.

The magnesium stearate (C₃₆H₇₀MgO₄) (CAS 557-04-0) used was a white to slightly yellow powder. The magnesium content was 3.8–5.0%. Magnesium stearate is among other things used as a paint and varnish drier, binder and emulsifier.

**Dustiness and dustiness testing**

Dustiness of the powders was determined with a rotating drum tester (EDT 38 L; JS Holdings, UK), provided with porous metal size-selective foams. The dustiness tester consists of the following sections (Burdett et al., 2000):

- a dust generation section, consisting of a stainless steel drum with eight blades on the internal wall,
- a transfer section and
- a sampling section.

A standard volume of material (35 ml) was placed in the drum and agitated for 65 s by rotation of the drum (4 r.p.m.). This procedure was repeated three times (i.e. total of three runs with the same set of foams and filter). The generated airborne dust is transferred from the generation section (drum) into the sampling section (air flow is 38 l min⁻¹), which separates the dust by aerodynamic particle sizes. The dust is collected on two nickel coated PE foams of 20 ppi (pores per inch), one nickel coated PE foam of 80 ppi and a glass fibre filter (Whatman GF/A reinforced ream, ID 130 mm and OD 150 mm, APFA 09050, 80 mm; Millipore Ltd) for gravimetric analysis. The foams have a diameter of 80 mm and a thickness 10 mm (Dunlop Ltd). The incoming air of the drum was filtered with a glass fibre filter (Whatman GF/A reinforced ream, 150 mm). Prior to the tests, the drum was ‘conditioned’ with the substance to be tested to prevent surface adhesion on the inner wall of the drum, i.e. a run was done before actually testing so a part of the substance can deposit on the inner wall of the drum. The mass of dust collected in the various size fractions after three runs was used to calculate the mass collected for each of the three biologically relevant size fractions.

The dustiness of the powders is determined by weighing the foams and filter of the dustiness tester. Weighing was performed with a calibrated balance with a reproducibility of ±0.1 mg (Mettler AT 200) according to a standard procedure, i.e. after at least 24 h of acclimatization, the foams and filters were weighed 3 days prior to the dustiness test and 3 days after the dustiness test. The weighing room was not controlled for temperature and humidity. The increase in weight was determined by the difference in the average weights before and after the dustiness test. The results of three tests were averaged and expressed as dustiness mass fractions, i.e. inhalable (Wᵢ), thoracic (Wₜ) and respirable (Wᵣ), according to CEN/TC 137 WG3, 2004). The results are given in Table 1. According to the classification for inhalable dustiness mass fractions, as proposed by CEN TC 137/WG 3 (2004), magnesium stearate was classified as having high dustiness (Wᵢ > 5000 mg kg⁻¹), whereas aluminium oxide and calcium carbonate were classified having low (200 < Wᵢ < 1000) and very low dustiness (Wᵢ < 200 mg kg⁻¹), respectively. Talc was used as an (internal) standard reference substance to check consistency of performance of the rotating drum over time and as a benchmark for comparing with results of others, e.g. Burdett et al. (2000) and CEN (2004).

**Inhalation exposure sampling**

Two devices commercially available for size-selective measurement of inhalation exposure were used to assess personal inhalation exposure. The first

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Table 1. Dustiness mass fractions of test substances (AM ± SD; n = 3). Indices I, T and R represent the dustiness of the inhalable, thoracic and respirable fraction, respectively.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Wᵢ (mg kg⁻¹)</th>
<th>Wₜ (mg kg⁻¹)</th>
<th>Wᵣ (mg kg⁻¹)</th>
<th>Dr (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium stearate</td>
<td>7214 ± 2083</td>
<td>2654 ± 1041</td>
<td>294 ± 221</td>
<td>3.7 ± 1.9</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>824 ± 178</td>
<td>237 ± 59</td>
<td>17&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.1 ± 0.7&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>147&lt;sup&gt;b&lt;/sup&gt;</td>
<td>101&lt;sup&gt;b&lt;/sup&gt;</td>
<td>23&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Reference substance</td>
<td>4428 ± 425</td>
<td>1862 ± 320</td>
<td>537 ± 406</td>
<td>12.5 ± 9.8</td>
</tr>
</tbody>
</table>

<sup>a</sup>Dr is the respirable fraction as a percentage of the inhalable fraction.

<sup>b</sup>Values calculated with half of the LOD.
Chemical analysis

To get a low limit of quantification compared to weighing, exposure samples were analysed chemically. After sampling the foams and filters were removed from the IOM cassettes, and filters from the impactor stages, respectively, and stored under environmental conditions prior to chemical analysis. The samples were extracted by boiling with 5 ml of nitric acid. Water was added to the solutions up to 50 g. The resulting solutions were determined for the content of calcium and magnesium using inductively coupled plasma atomic emission spectrometry (ICP-AES) at wavelengths of 393 and 279.5 nm, respectively. Calibration samples of 1000 mg l−1 were prepared by adding different concentrations of a commercial aluminium standard solution to 100 ml with diluted hydrochloric acid.

To analyse the samples, an ICP-AES type IRIS Intrepid with auto sampler was used.

The calibration curves were determined and consisted of at least four standard solutions and a blank. The correlation coefficient was calculated.

The limit of detection (LOD) and quantification (LOQ) were determined by analysing blank matrices. The LOD was defined as three times the standard deviation of the concentration of the average of two blank solutions. The LOQ was 10 times the standard deviation. LOQs for magnesium stearate, aluminium oxide and calcium carbonate were 24, 79 and 4 μg, respectively.

Statistical analysis

Statistical analyses were conducted using SAS statistical software (version 8.1; SAS Institute, Cary, NC, USA). Inhalation exposure was presented as arithmetic mean, geometric mean and geometric standard deviation. Values below LOQ were replaced with values 1/2 times LOQ. The Wilcoxon two-sample test was used to study the difference in dust exposure between the substances handled (two-sided; ɑ<0.05). Wilcoxon scores generated under PROC NPAR1WAY using the SAS 8.1 System corresponds to the Mann–Whitney U-test if data are classified in two levels. PROC REG procedure was used to investigate the relationship between dependent variable (log-transformed exposure values) and the independent variables, substance (dummy), scenario (dummy) and dustiness as indicated by inhalable dustiness mass fractions.

RESULTS

During the experiments daily averages of temperature, relative humidity and air exchange rates were in the ranges 18.5–21.5°C, 40–59% and 0.7–1.8, respectively. Details are presented in Table 2.

Descriptives of the exposure levels as determined by IOM MultiDust sampler are given in Table 3. Statistically significant differences in dust exposures were observed between handling magnesium stearate and aluminium oxide, and magnesium stearate and calcium carbonate, respectively (Table 4). The differences in exposure between the two exposure scenarios were not statistically significant with exception of inhalable dust exposure during handling aluminium oxide.
Descriptives of exposure levels as determined by the RespiCon® sampler are given in Table 5. Except for the inhalable fraction of calcium carbonate, all means for RespiCon® data are slightly lower than that of the IOM MultiDust data.

Based on IOM MultiDust inhalation and respirable exposure data for magnesium stearate the mean respirable fraction was 6.1% (SD = 2.3; n = 10) of the inhalable fraction, excluding two outliers. Based on Respicon® data the respirable fraction was 8.1% (SD = 6.0; n = 4) According to the calculated dustiness mass fractions based upon the dustiness tests the respirable fraction was 3.7 (±1.9)% of the

<table>
<thead>
<tr>
<th>Day</th>
<th>Room 1 (sweeping/cleaning)</th>
<th>Room 2 (weighing/adding)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>1</td>
<td>21.4</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>20.8</td>
<td>47</td>
</tr>
<tr>
<td>3</td>
<td>19.4</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>20.2</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>20.2</td>
<td>40</td>
</tr>
</tbody>
</table>

*n.a., not available: door was opened during tracer gas measurements.

Table 3. Exposure levels (IOM MultiDust) during use of substances with varying inhalable dustiness mass fractions

<table>
<thead>
<tr>
<th>Substance</th>
<th>$W_1$</th>
<th>Scenario</th>
<th>$N$</th>
<th>AM (mg m$^{-3}$)</th>
<th>GM (mg m$^{-3}$)</th>
<th>GSD</th>
<th>Range (mg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inhalable exposure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium stearate</td>
<td>0.72</td>
<td>Cleaning/sweeping</td>
<td>6</td>
<td>199.9</td>
<td>191.1</td>
<td>1.4</td>
<td>99.2–252.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>210.7</td>
<td>171.0</td>
<td>2.4</td>
<td>31.9–313.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>205.3</td>
<td>180.7</td>
<td>1.9</td>
<td>31.9–313.1</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>0.08</td>
<td>Cleaning/sweeping</td>
<td>6</td>
<td>9.1</td>
<td>8.1</td>
<td>1.7</td>
<td>5.2–16.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>58.6</td>
<td>52.3</td>
<td>1.7</td>
<td>21.1–91.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>33.9</td>
<td>20.6</td>
<td>3.0</td>
<td>5.2–91.2</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.01</td>
<td>Cleaning/sweeping</td>
<td>6</td>
<td>17.2</td>
<td>16.5</td>
<td>1.4</td>
<td>8.9–23.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>10.4</td>
<td>9.9</td>
<td>1.4</td>
<td>5.6–15.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>13.8</td>
<td>12.8</td>
<td>1.5</td>
<td>5.6–23.3</td>
</tr>
<tr>
<td><strong>Respirable exposure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium stearate</td>
<td>0.72</td>
<td>Cleaning/sweeping</td>
<td>6</td>
<td>13.4</td>
<td>12.9</td>
<td>1.4</td>
<td>6.4–16.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>37.7</td>
<td>11.9</td>
<td>5.5</td>
<td>0.9–174.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>25.6</td>
<td>12.4</td>
<td>3.2</td>
<td>0.9–174.7</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>0.08</td>
<td>Cleaning/sweeping</td>
<td>6</td>
<td>4.4</td>
<td>3.2</td>
<td>2.1</td>
<td>2.0–13.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>27.5</td>
<td>9.6</td>
<td>5.8</td>
<td>2.0–77.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>15.9</td>
<td>5.6</td>
<td>4.1</td>
<td>2.0–77.8</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.01</td>
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<td>3.2</td>
<td>3.1</td>
<td>1.3</td>
<td>2.6–4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scooping/transfer</td>
<td>6</td>
<td>2.5</td>
<td>2.4</td>
<td>1.3</td>
<td>1.9–3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All</td>
<td>12</td>
<td>2.8</td>
<td>2.7</td>
<td>1.3</td>
<td>1.9–4.9</td>
</tr>
</tbody>
</table>

$^aW_1 = $ dustiness mass fraction – inhalable fraction.

$^b$Value based on foam <LOQ, and filter <LOD.

$^c$Of six foams, five were <LOQ for cleaning/sweeping.

$^d$One foam <LOD, however large amount on filter.

$^eN = 3 <$ LOD and $N = 2 <$ LOQ.

$^fN = 3 <$ LOD, on one filter a large amount was found (filter belonging to foam containing an amount of <LOD, see d).

Table 4. Results of Wilcoxon tests for pooled IOM MultiDust data (all scenarios)

<table>
<thead>
<tr>
<th>Substances</th>
<th>Size fraction</th>
<th>Significance ($P$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium stearate – calcium carbonate</td>
<td>Inhalable</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Magnesium stearate – aluminium oxide</td>
<td>Respirable</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>Aluminium oxide – calcium carbonate</td>
<td>Respirable</td>
<td>&lt;0.012</td>
</tr>
</tbody>
</table>

n.s., not significant.
inhalable fraction. In addition, Respicon® data revealed a thoracic fraction of 41 (±9)% of the inhalable fraction, whereas the thoracic dustiness mass fraction was 36.2 (±4.8)% of the inhalable dustiness mass fraction.

Analysis of regression of inhalable exposure data (IOM) for both scenarios showed that dustiness was a significant parameter whereas scenario was not a significant parameter. Dustiness explained ~70% of the variance of exposure, i.e. $R^2$ adjusted = 0.695 (Fig. 1).

**DISCUSSION**

**Dustiness**

The type of rotating drum dustiness tester used in the present study is provided with metal coated foams. The weight of the foams affects the LOD
(LOD = 12 mg) and limits the accuracy of the test results. For the substances with low to very low dustiness, i.e. aluminium oxide and calcium carbonate, respectively, this resulted in some individual foam and filter weights being below LOD, and inaccurate data for the respirable fraction of aluminium oxide and all fractions of calcium carbonate. For this reason we could not compare the respirable fraction of dustiness with respirable exposure as we did for the inhalable fractions. Currently, the LOD has decreased with a factor 10 by improved weighing conditions, including elimination of electrical charge, and substitution of the balance.

Relative standard deviations [RSD: calculated as (SD/mean) × 100%; n = 3] of dustiness for the inhalable dustiness mass fraction based on the data given in Table 1 were 29 and 22% for magnesium stearate and aluminium oxide, respectively. These RSDs are in line with ranges of 16–39% (outlier 105%) as reported by Burdett et al. (2000) for test results (six substances) using a similar rotating drum tester equipped with PE foams. The same holds for the RSDs for the thoracic and the respirable fractions; however, RSDs observed in the present study are at the upper side of the distribution.

RSD of talc (reference substance) was very low (<10%); however, the numbers of replicates for this substance (n = 7) were high compared to the test substances. The inhalable mass fraction of 4428 mg kg⁻¹ indicates a moderate dustiness for talc according to the CEN TC 137 WG3 classification. Additional testing of talc and aluminium oxide reference substances used by Burdett et al. (2000) revealed results close to the dustiness fractions of the talc and aluminium oxide used in the present study. This observation indicates good compatibility of both test method and reference substances.

The range of dustiness covered by the three test substances was close to the range of inhalable dustiness mass fractions measured in the EU project SMT4-CT96-2074 and included in CEN TC 137 WG3 document, i.e. 170–9000 mg kg⁻¹. However, the difference between aluminium oxide and calcium carbonate was small (Fig. 1). Only a small and non-significant difference in mean exposure between these two substances was observed.

**Exposure**

Measurements with the RespiCon® were included, since this is the only commercially available device to measure exposure for all three biologically relevant fractions simultaneously. However, the numbers of measurements were limited so the results are only indicative. IOM MultiDust device results were used to compare exposure with dustiness.

Exposure levels measured in the present study were high [range GM inhalable dust (all scenarios) was 8.1–191.1 mg m⁻³]. The high exposure levels can be explained by the design of the experiment, i.e. small rooms with practically no ventilation.

A tendency for a higher level of exposure during the cleaning/sweeping scenario could be observed for two out of the three substances (Table 3). For aluminium oxide significant higher exposures were observed during the scooping/transfer scenario. The grainy structure of aluminium oxide compared to both other substances might contribute to this phenomenon; however, it remains unclear. In nearly all cases the variability of dust exposures (GSDs) during scooping were higher compared to exposure during the cleaning scenario. Table 3 shows that GSDs for IOM inhalable dust fraction results are moderate (up to 3.0), whereas as GSDs for the respirable fraction are relatively high (up to 5.8), mainly due to the large numbers of non-detects.

Except for the inhalable fraction of calcium carbonate (scooping scenario), RespiCon® results showed lower concentrations compared to the results obtained by the IOM MultiDust sampler (Tables 3 and Tables 5). These observations are well in line with the results of the CALTOOL project (Mark et al., 2004), where the geometric means of the performance ratio of both samplers compared to a reference sampler were 1.33 and 1.06 for the IOM MultiDust sampler and the RespiCon®, respectively. Bråtveit et al. (2004) also reported significantly higher concentrations for the (conventional) IOM sampler compared to the RespiCon® for the inhalable fraction. Koch et al. (2002) proposed a correction fraction for RespiCon®'s thoracic and inhalable fractions to compare results between both samplers.

The relevance of size-selective determination of dustiness is illustrated by the similarity of the contribution of the respirable fraction to dust concentrations in the breathing zone during handling compared to dustiness. The percentage of the respirable dust of the inhalable fraction was just slightly higher in the breathing zone compared to the ratio of inhalable and respirable dustiness. Since larger particles will deposit earlier compared to small particles, the particle-size distribution at a distance from an emission point will show relatively larger numbers of small particles.

**Relationship of dustiness and exposure**

The relationship between dust generating properties of substances and dust emission and worker exposure during operations has been previously explored. Cowherd et al. (1989) investigated the process of emission during pouring operations of small volumes of powder under controlled conditions. For four substances tested the ranking of both emission factors and the respirable dust concentrations during pouring operations compared well with the dustiness of the substances as determined by the Midwest Research Institute (MRI) single drop dustiness tester.
that is aimed at simulating the pouring and dumping of fine solids.

Heitbrink et al. (1989, 1990) applied dustiness tests to predict worker dust exposure for (large volume) bagging operations. The dustiness of six bulk materials was assessed by two dustiness testers (Heubach rotating drum and the MRI tester). Both types of dustiness testers do not distinguish health-related dust fractions. Workers inhalation exposures were assessed using a standard filter pump method to estimate the inhalable fraction. For bag packaging operations linear regression analysis revealed a statistical significant relationship between dustiness and the ln-transformed dust exposures with $R^2$ of 0.59 and 0.45 for Heubach and MRI dustiness indices, respectively (Heitbrink et al., 1989). For bag filling and bag dumping operations results were less consistent. Only for a bag filling site a significant correlation between dustiness and workers exposure could be observed, whereas for a bag dumping operation the Heubach dustiness test results needed to be adjusted for drop height to find a significant correlation.

The results of the present study clearly indicate that for manual small volume powder operations such as scooping/transfer and cleaning/sweeping the dustiness as determined by the rotating drum dustiness tester is a major determinant of exposure. However, in workplace practice factors that have been controlled in the present study such as drop height, total volume handled, ventilation or individual work habits will also determine exposure (Cowherd et al., 1989). Therefore, more field studies are needed to evaluate the correlation between dustiness test results and dust exposure for various processes of airborne dust generation, in order to enable the use of dustiness as a parameter in predictive exposure models.

Results of studies on dustiness and dust exposure, including the present one, emphasize the strong potential to classify substances according to dustiness. First of all dustiness tests provide a useful indication of the relative exposure potential of different powders. In addition, it provides a tool to develop and test low dust alternatives. Especially combining hazardous effects and biologically relevant size fractions, emphasis can be given to suppress dust generation of an identified relevant fraction. Dustiness mass fractions can also be used for sales or marketing purposes to document low dust alternatives or substitutes to own or competitors products. Moreover, dustiness mass fractions may be more relevant for risk assessment in view of new and existing substance regulations than particle size distribution. The results of the present study will contribute to a more extensive application of dustiness parameters; however, additional research, e.g. similar experiments with more substances including substances with inhalable dustiness mass fractions between the lower and upper end of the range of the present study, i.e. between 1000 and 7000 mg kg$^{-1}$ is needed.

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