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A new dust generator for laboratory dust emission studies

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ABSTRACT

The aim of this study was to develop a cheap and replicable dust generator for production and investigation of fugitive dusts. We call the device the Easy Dust Generator (EDG). The EDG was constructed with common materials widely available in any laboratory so that it can be replicating anywhere in the world. In order to evaluate the performance of EDG, six repetitions of dust emissions on clay loam, sandy loam, loamy sand, and silt loam soils were measured. According to Gill et al. (2006), the EDG is a “Class C” dust generator. The emission curves obtained with EDG were similar to those obtained with other “Class C” dust generators such as the Lubbock dust generation sampling and analysis systems (LDGASS) and the Southard Laboratory dust generator, but with some differences in the absolute values. Maximum PM_{10} concentration was higher in fine texture than in coarse-textured soils. The average PM_{10} concentration and PM_{10} emissions per grams of soil ordered in the sequence loamy-sand < sandy loam < silt loam < clay loam. These results are in agreement with previous studies where PM_{10} emissions were higher in fine soils than in coarse soils. The standard deviation (SD) of the averaged PM_{10} concentration of all analyzed soils varied between 10% and 13%, being these values similar to those reported using other dust generator (from 6% to 24%). We concluded that the EDG can be reproduced anywhere in the world by using common materials and reliable PM_{10} emission measurements with good repeatability.

1. Introduction

A challenge of agriculture is to increase food production with the least environmental impact while preserving the natural resources. Agricultural activities release particles to the atmosphere with aerodynamic diameters smaller than 10 µm (PM_{10}) which have negative effects on the environment and human health (Prospero et al., 1983; Larney et al., 1998; Grantz et al., 1998; Norton and Gunter, 1999). The main sources of these particles are wind erosion, tillage operations and traffic on unpaved roads (Saxton, 1995; Chow et al., 1992; Holmen et al., 2001; Goossens and Buck, 2009). In all these cases, besides the natural soil emission capacity, other processes like the friction between particles or the breakdown of soil aggregates, can contribute to create larger amounts of PM_{10} than preexistent.

Field dust emission studies are time consuming and expensive. Furthermore, in field studies, the soil and climatic variability cannot be controlled. Field wind tunnel studies are an alternative to control time and wind velocity of an erosive event, but some other variables like soil moisture, soil homogeneity and temperature are difficult to control. Because of that lab studies with dust generators, which allow this kind of studies under controlled conditions, are an important method for determining the emission potential of different dust sources, their physical characteristics, chemical composition and environmental health and toxicological effects of the particulate matter emitted from different sources.

According to Gill et al. (2006), dust generators are classified as follows: based on fluidization (gas dispersion or ventilation), gravitation (drop or “impact” method) and mechanical dispersion or agitation (rotating drum and similar techniques). The fluidization generator simulates the direct suspension or re-suspension of pre-existing, loosed-fine particles from a solid surface under static conditions by drag or lift forces, but it does not transfer mechanical or kinetic energy to dust source materials (Gill et al., 2006). The gravitation and mechanical dispersion or agitation generator has been widely used to estimate the PM_{10} emission by wind erosion, tillage operations and traffic on unpaved roads. This kind of device transfers mechanical or kinetic energy to dust source materials, creating aerosols from the abrasion or fracture caused when grains of the source material collide with each other and/or the dust generator.

There are many commercial dust generators available, but the cost of those devices is several thousand of US dollars. There are also many non-commercial dust generators. Many of these require substantial engineering fabrication, some of them have not been

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calibrated and others lack sufficient construction details. According to Gill et al. (2006), relatively few systems have been strictly utilized for production and investigation of fugitive dusts or mineral aerosol for atmospheric particulate matter research. Two examples of non-commercial dust generators, developed for production and investigation of fugitive dusts or mineral aerosol, are the dust generation, sampling and analysis systems (LDGASS, Gill et al., 1999, 2006) and the Southard Laboratory dust generator (Domingo et al., 2010).

The LDGASS has been designed to simulate wind erosion of soils and sediments under field conditions, collecting a small portion of a large cloud of polydisperse dust aerosol from a relatively large source sample (Gill et al., 1999). The LDGASS consists of three separate modules. In the first one, dust is generated by applying energy to a bulk source sample by gravitation or mechanical dispersion. The "dust generation" module of the system comprises a small "dustfall tube" (gravitation dust generator). Entrained dust flows into an analysis module of the system, passing through the beam of a laser diffraction particle sizer (Malvern Instruments) located approximately 0.5 m downstream from the exit of the dust generator. Suspended aerosol flows an additional 0.3 m into a settling module for sampling $PM_{2.5}$ on an impactor and measuring dust concentration via a forward-scattering nephelometer (Gill et al., 2006).

The Southard Laboratory dust generator developed by Domingo et al. (2010) consists of two major components: the rotating chamber and the settling chamber. The rotating chamber has three steel baffles welded perpendicular to the interior drum surface. The rotating chamber rests on rubber wheels connected to a motor to rotate the steel drum. A blower is connected to a tube, which is threaded through the center of the rotating drum and penetrates the interior of the settling chamber. Inside the settling chamber, a small fan with blades helps to distribute the dust and in the upper portion of the settling chamber there are holes through which air pumps are connected to dust samplers (Domingo et al., 2010).

The not commercial dust generators described above require substantial engineering fabrication and their cost can be height. In view of this restriction the aim of this study was develop a cheap and replicable dust generator for the quantification of fugitive dusts or mineral aerosols.

2. Materials and methods

2.1. Easy Dust Generator (EDG) description

The EDG is composed by two parts: (1) a dust generating chamber and (2) a concentration chamber (Figs. 1 and 2).

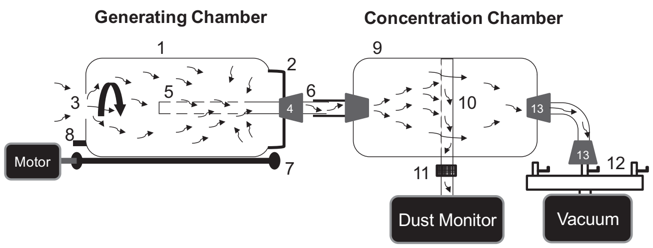

Fig. 1. Schematic of the Easy Dust Generator (EDG). where, 1 plastic bottle of the generating chamber, 2 screw cap, 3 orifice, 4 rubber stopper, 5 plastic tube with holes, 6 connection between the generation chamber and the concentration chamber, 7 mobile cylinder, 8 passive cylinder, 9 plastic bottle of the concentration chamber, 10 plastic tube, with holes, connecting the concentration chamber to dust monitor, 11 filter, 12 pipes with taps, 13 rubber stoppers. The bigger arrow shows the Generating Chamber rotation and the smaller arrows show the air circulation.

Fig. 1 shows a schematic of the Easy Dust Generator (EDG). The generating chamber, where the soil sample is placed, consists of a 116 mm wide and 200 mm tall plastic bottle (used for food storage) (1). Within this bottle, four 50 × 200 mm plastic blades (made with hard plastic) are installed with an angle of 30° to the bottle surface (Fig. 3). To install the blades the screw cap was removed (2). The blades mix the soil sample during bottle rotation. A 21 mm diameter orifice on one bottle extreme allows the free entrance of the air and is used to introduce the soil sample (3). On the other side of the bottle an 8 mm diameter plastic tube is inserted through a rubber stopper which is placed in a 21 mm diameter orifice avoiding air losses (4). The portion of the plastic tube inside the generating chamber has 4 rows of 5 holes (2 mm diameter) placed 15 mm apart along the tube (5). The rows are placed perpendicularly each other over the plastic tube. The portion of the plastic tube outside the generating chamber is coupled to a glass tube connected to the concentration chamber (6). This mechanism allows the rotation of the generating chamber while the concentration chamber is stationary.

The generating chamber rests on two cylinders: a 270 mm long and 32 mm wide mobile one (in this case a commercial printer cylinder) and a 270 mm long and 10 mm wide passive cylinder (in this case a glass tube which rotates freely over a 270 mm long and 8 mm wide solid pipe) (7 and 8). A small electric motor (Zhaoqing Wei Li Co., LTD, AC: 220 V/240 V–50/60 Hz–4 W) rotates the mobile cylinder at 30 rpm, which moves the generating chamber at 6 rpm. The cost of this motor ranges from 10 to 15 US dollars, depending on their rotation velocity.

The concentration chamber is a 116 mm wide and 250 mm long plastic bottle (9). Within this chamber a 9 mm diameter and 150 mm long plastic tube is placed in the middle of the concentration chamber, perpendicularly to its main axis (10). This plastic tube has a row of 8 orifices of 2 mm diameter and 15 mm apart. This plastic tube connects the concentration chamber with a PM_{10} dust monitor, in this case a Kanomak model 3442. The hose connecting the concentration chamber with the PM_{10} dust monitor has a filter 0.074 mm mesh to retain larger particles that can damage the dust monitor (11).

A vacuum source is connected to the distal extreme of the concentration chamber through a 10 mm diameter pipe. Three pipes with taps connect the concentration chamber with the vacuum source (12). The taps allow the regulation of the air flux aspirated by the vacuum bomb, which maximum aspiration capacity is $4.3 \times 10^{-3}\ m^3\ min^{-1}$. The plastic tube that connects the concentration chamber and the vacuum bomb has two rubber caps that seal the connection (13).

2.2. EDG operating mode

The soil sample (1.5 g), previously sieved by 0.5 mm without crushing the material, is dropped inside the generating chamber. This amount of soil was choosing because it generated a PM_{10} concentration that did not exceed the dust monitor detection range of 10 mg m^{-3}. The soils were passed through a 0.5 mm diameter sieve in order to avoid the interference of large aggregates of more developed and structured soils and to make PM_{10} emission comparable among soils. According to Gill et al. (2006) some dust-generating systems use more or less undisturbed soil samples, while others sieve or pre-separate the source materials like the LDGASS (Amante-Orozco, 2000) and the UC Davis re-suspension test chamber (Carvacho et al., 2004). Once sieved, the soil sample is dropped into the generating chamber, and the dust monitor, the vacuum source and the electric motor are sequentially switched on. The generating chamber rotates and transports the soil sample from the bottom to the top, from where it falls (Fig. 3). During the fall, the dust particles collide and impact with the chamber wall,

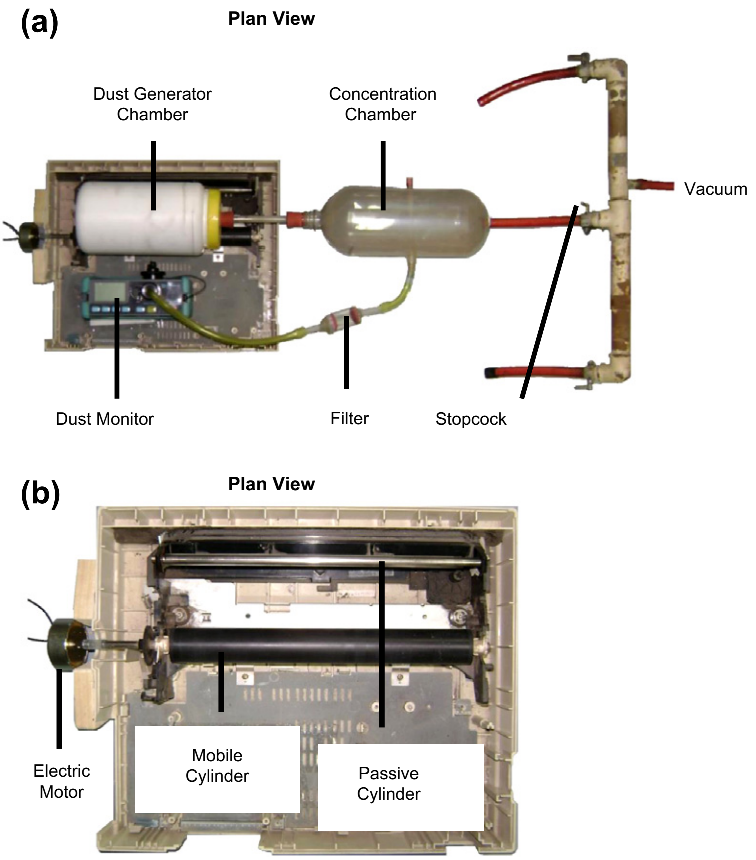

Fig. 2. View of the Easy Dust Generator (EDG). (a) Entire plan view of the EDG and (b) Details plan view of the moving mechanism.

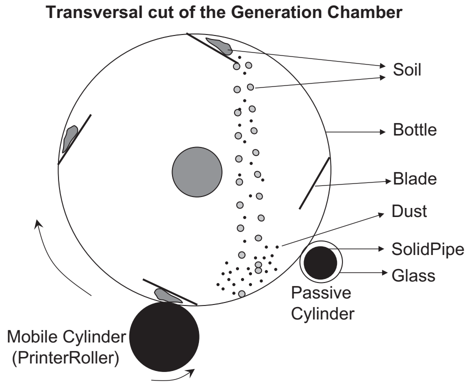

Fig. 3. Transverse view of the generating chamber and moving parts.

producing new dust particles. The released dust is transported to the concentration chamber by the air flow produced by the vacuum pump. The air loaded with PM_{10} particles entering to the concentration chamber are lately aspirated by the dust monitor, which measures PM_{10} concentrations. The remaining air continues to the vacuum pump where it is discharged outside the system. The dust monitor must be regulated to measure and register the average PM_{10} concentration (expressed in mg m^{-3} of air) each 6 s (Fig. 1). The dust monitor counts the particle number during 6 s and then divides this by the air volume aspirated in 6 s. The Kanomak model 3442 is a light scattering digital dust monitor with a particle range from 0.1 to 10 μm, flow rate 1 l min^{-1} and measuring range from 0.001 to 10000 mg m^{-3} (more details of the dust monitor can be found in www.kanomax-usa.com).

2.3. EGD calibration

Dust emissions of air-dried soils with contrasting textures (a clay loam, a sandy loam, a loamy sand, and a silt loam) were measured in order to evaluate the sensibility of EDG. In order to characterize each soil, the organic matter (OM, Walkley and Black, 1934) and the texture (Gee and Bauder, 1986) were measured, and the geometric mean diameter was calculated (Table 1). The repeatability of the device was evaluated measuring the dust emission of each soil six times. The coefficient of variation between repetitions was calculated with Microsoft Excel. The evolution of PM_{10} concentrations with time (emission curve), the averaged PM_{10}

Table 1
Soils properties.

Soil properties	Units	Soil type			
		Clay loam	Silt loam	Sandy loam	Loamy sand
Clay (<2 μm)	%	28.4	21.3	12.9	6.8
Silt (2–50 μm)		50.1	50.2	19.7	17.9
Total sand (50–2000 μm)		21.5	28.5	67.3	75.2
Very fine sand (50–73 μm)	%	8.2	15.1	12.3	8.1
Fine sand (73–100 μm)		6.2	8.6	17.6	10.9
Medium sand (100–250 μm)		5.8	4.8	28.2	31.4
Coarse sand (250–2000 μm)		1.3	0.1	9.3	24.8
Geometric mean diameter	μm	4.7	10.0	63.0	98.0
Organic matter (OM)	%	3.3	5.5	2.7	2.0

concentration along the experiment, the maximum PM_{10} concentration and the total PM_{10} emission were also analyzed.

The total PM_{10} emission, expressed in milligrams of PM_{10} per gram of soil was calculated with the following equation:

$$TE_{PM_{10}}\ (\text{mg g}^{-1}) = \frac{PM_{10}\ \text{ave} \times \text{VARB} \times \text{DE}}{\text{PMS}} \quad (1)$$

where $TE_{PM_{10}}$ is the total PM_{10} emission in mg g^{-1} of soil, PM_{10} ave is the averaged PM_{10} concentration along the experiment in mg m^{-3} of air (sum of the dust monitor records divided by the amount of air passing through the dust monitor 6 s), VARB is the air volume removed by the vacuum pump in m^3 min^{-1}, DE is the experiment duration in min, and PMS is the soil sample weight in g.

The total PM_{10} emission expressed in percentage was calculated with the following equation:

$$\begin{aligned} TE_{PM_{10}}(\%) &= \frac{TE_{PM_{10}}(\text{mg g}^{-1}) \times 1(\text{g})}{1000(\text{mg})} \times 100 \\ &= TE_{PM_{10}}(\text{g g}^{-1}) \times 100 \end{aligned} \quad (2)$$

where $TE_{PM_{10}}$ (%) is the total PM_{10} emission in percentage, $TE_{PM_{10}}$ (mg g^{-1}) is the total emission in milligrams of PM_{10} by gram of soil and $TE_{PM_{10}}$ (g g^{-1}) is the total emission in grams of PM_{10} by gram of soil.

3. Results and discussion

According to the classification of Gill et al. (2006), the Easy Dust Generator (EDG) is a generator "Class C". The EDG is a mechanical agitation generator which releases loose dust from a soil sample and also as a product of the abrasion or the fracture caused by grains collision with each other and/or against the wall of the generator. The "Class C" dust generators have been widely used to estimate the PM_{10} emission by wind erosion, tillage operation and unpaved road traffic (Gill et al., 2006).

The EDG uses the same principles of applying kinetic energy to a soil sample and has a rotating chamber connected to a settling chamber as both, the dust generation, sampling and analysis systems (LDGASS, Gill et al., 1999) and the Southard Laboratory Dust Generator (Domingo et al., 2010). Our system has similar constructive details as the Southard Laboratory Dust Generator. However, the EDG uses few grams of soil while the Southard Laboratory Dust Generator uses one hundred to several hundred grams of soil. In the EDG, the air loaded with suspended particulate matter is aspirated while in the Southard Laboratory Dust Generator the air is blown. Besides, the air sampling inside of the concentration chamber (settling chamber in the Davis California system) is substantially different between the EDG and the Southard Laboratory Dust Generator. The Southard Laboratory Dust Generator has a diffuser that helps the dust entering the settling chamber to be dispersed, it has a small fan that distributes the dust evenly throughout the chamber and the dust is collected on filters suspended in the settling chamber. The filters are connected to vacuum pumps attached to the outside of the settling chamber via sampling ports (Domingo et al., 2010). In the EDG, dust sampling is taken through a plastic tube placed in the middle of the concentration chamber, perpendicular to its main axis.

Fig. 4 shows a representative emission curve for each analyzed soil. The general trends of PM_{10} emission curves of all analyzed soils were similar: during the first 180 s PM_{10} concentrations increased linearly rapidly, until reaching the maximum PM_{10} concentration. After this point, PM_{10} concentration decreased in an exponential way until reaching a constant PM_{10} concentration level (stabilization zone).

The time-dependant emission curves obtained with the EDG were similar to those described by Amante-Orozco (2000), who

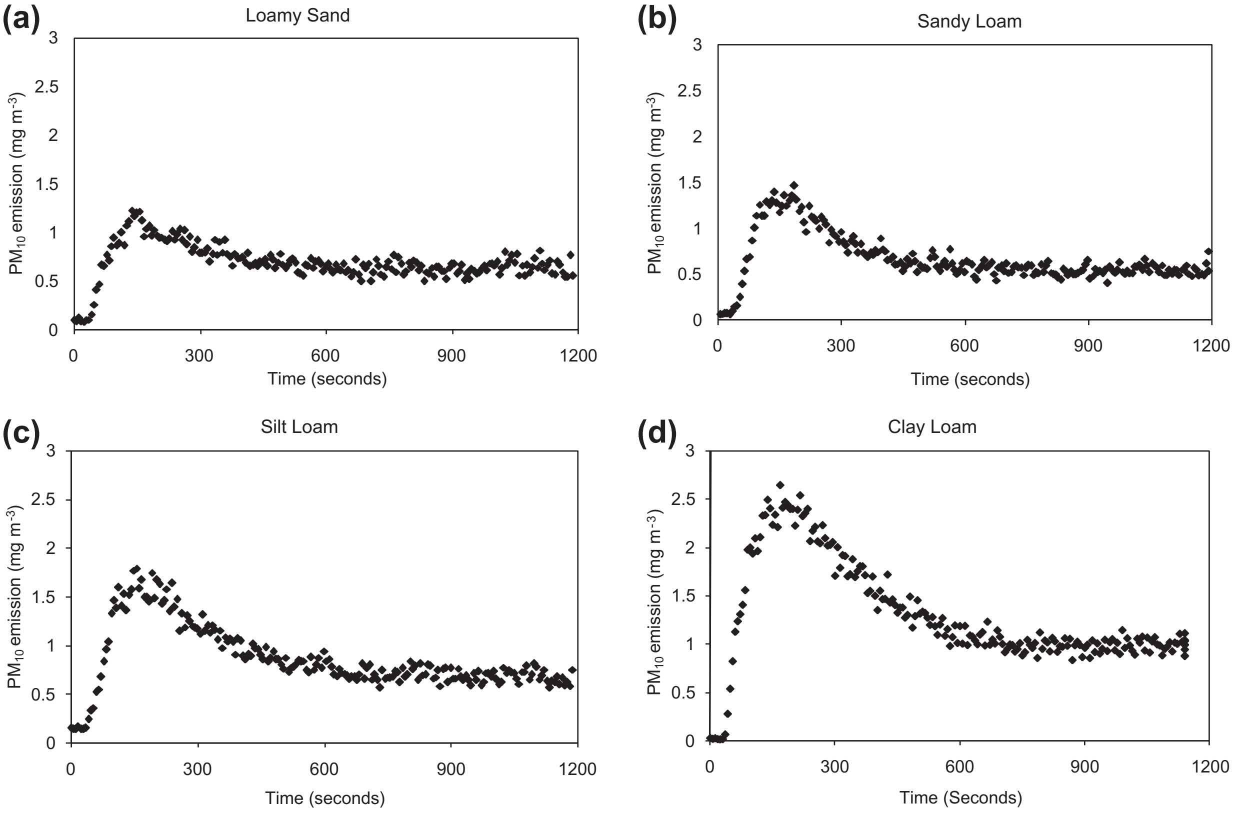

Fig. 4. PM_{10} emission as a function of time for (a) a loamy sand, (b) a sandy loam, (c) silt loam and (d) clay loam.

Table 2
Maximum PM_{10} concentration, average PM_{10} concentration, total PM_{10} emission and standard deviation of the average PM_{10} concentration.

Soil type	PM_{10} max	PM_{10} ave		Total PM_{10} emission	
		$mg\ m^{-3}$	CV (%)	$mg\ g^{-1}$ soil	%
Loamy sand	1.29^a	0.67^a	12	65.9^a	6.6^a
Sandy loam	1.85^b	0.76^b	10	75.2^b	7.5^b
Silt 1	1.86^b	0.88^b	13	86.3^b	8.6^b
Clay loam	2.50^c	1.26^c	10	124.4^c	12.4^c

Where: PM_{10} max = maximum PM_{10} concentration, PM_{10} ave = average PM_{10} concentration, CV = coefficient of variation. Values with different letters indicate differences between soils ($p < 0.01$).

used the LDGASS and Domingo et al. (2010) who used the Southard Laboratory Dust Generator. Amante-Orozco (2000) found that PM_{10} concentrations increased during the first 90 s, time at which the maximum PM_{10} concentration was reached. After that time, the PM_{10} emission decreased slowly until reaching the “stabilization zone”. Maximum PM_{10} concentrations reported by Amante-Orozco (2000) were 40 mg m^{-3} in a sandy soil and 45 mg m^{-3} in clay loam soil, from a 25 g soil sample. Domingo et al. (2010) found that PM_{10} concentrations increased during the first 180 s, from 300 g Reiff loam soil samples (42% sand, 39% silt, and 19% clay) with initial gravimetric water content of 10% during a 10 min sampling period. After that time, PM_{10} concentration decreased slowly until reaching the “stabilization zone”. PM_{10} concentration reported by Domingo et al. (2010) was 35 mg m^{-3} for the Reiff loam soil. Those maximum PM_{10} concentrations reported by Amante-Orozco and Domingo, were 20–25 times higher than that reported in our study. The differences among studies must be attributed to the configuration of each dust generator (amount of soil sample, air flux rates, etc.). It is known that the amount of soil sample and the air flux rates change PM_{10} emission rates (Amante-Orozco, 2000).

The time elapsed to reach the “stabilization zone” in each soil was ordered in the sequence loamy sand < sandy loam < silt loam < clay loam (Fig. 4). Sandy soils reached the “stabilization zone” earlier than fine textured soils. This was a consequence of the lower OM- and clay contents of the sandy than the fine textured soils (Table 1). Studies have shown that OM- and clay contents are positively related to soil aggregation (Tisdall and Oades, 1982; Skidmore and Layton, 1992; Fryrear et al., 1994; Six et al., 2000). Less aggregated soils (sandy soils) have fewer PM_{10} particles forming aggregates and because of that they reached the “stabilization zone” in a shorter time. Fine textured soils, with better aggregation, have more PM_{10} particles into aggregates. Because of that their PM_{10} release is slower as this occurs only after aggregates destruction.

Table 2 shows the maximum and the averaged PM_{10} concentrations, the total PM_{10} emissions and the respective coefficient of variation of the average PM_{10} concentration for each soil. The maximum PM_{10} concentration was higher in fine- than in coarse textured soils. However, maximum PM_{10} concentration of the sandy loam and the silt loam soils were similar. This may be a consequence of the high organic matter contents (OM) of the silt loam soils (Table 1). In agreement with these findings, Aimar et al. (2011) showed that increasing OM reduces PM_{10} emissions as a consequence of its positive effect on soil aggregation. Our results are also in agreement with those of Amante-Orozco (2000) who found that maximum PM_{10} concentrations of soils ordered in the sequence fine sandy < sandy clay loam < clay loam. On the other hand, Madden et al. (2010), testing 23 soils with textures ranging from sandy to clayey, did not found any correlation between maximum PM_{10} concentrations and the contents of sand, silt, or clay.

The averaged PM_{10} concentration and the total PM_{10} emissions of soils analyzed here ordered in the sequence loamy-sand < sandy loam < silt loam < clay loam (Table 2). These results are in agreement with previous studies where PM_{10} emissions were higher in fine soils than in coarse soils (Amante-Orozco, 2000; Carvacho et al., 2004; Funk et al., 2008). According with our results and previous findings, fine textured soils have more capacity to emit PM_{10} than coarse-textured soils. However, many times, under natural conditions, fine textured soils have high amounts of non-erodible aggregates which limit PM_{10} emission by wind erosion. However, PM_{10} emission by mechanical disturbance increases when the silt/clay ratio increases (Madden et al., 2010).

The coefficient of variation (CV) of the averaged PM_{10} concentration of all analyzed soils varied between 10 and 13%, being higher in the sandy loam and clay loam than in the loamy sand and clay loam soils (Table 2). High coefficient of variation values were produced by the high variability in the soil composition and less by EDG operation deficiencies, for example errors during weighing of soil samples, changes in the air flux rates or changes in the rotation speed of the generator during measurements. That is supported by the coefficients of variation obtained in this study, which were similar to those reported in previous studies, obtained with other dust generator types. For example, Amante-Orozco (2000), reported coefficients of variation in soils ranging from fine sandy loam to clay loam, of 8–24%. Funk et al. (2008) using a conveyor belt to generate dust in a wind tunnel, reported coefficients of variation of 6% in sandy soils and 20% in clayey soil.

4. Conclusions

The EDG is a “Class C” dust generator that can be reproduced anywhere in the world by using common and inexpensive materials. The EDG gave reliable PM_{10} emission measurements with good repeatability. The PM_{10} emission measured with the EDG on soils of different textures followed similar tendencies as PM_{10} emissions measured with other dust generators, on soils of similar textures.

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