Guidelines for Measuring Particulate Matter at Construction Sites

Subjects: Engineering, Civil
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PM is a set of air pollutants consisting of solid or liquid particles. These particles are suspended in the atmosphere, but they can also be sedimented on surfaces. Despite a number of differences, PM is mainly classified by its aerodynamic diameter into three groups: (1) fine or breathable particles (PM2.5) with aerodynamic diameter up to 2.5 µm, (2) coarse or inhalable particles (PM10) with an aerodynamic diameter up to 10 µm, and (3) total suspended particles (TSP) that have a wide particle size range, typically with an equivalent aerodynamic cutting diameter of 100 µm.

air pollution particulate matter

1. Introduction

Construction sites are considered to be one of the main emitters of particulates in the environment, owing to the nature of their work procedures and the recurrent use of heavy machinery and equipment [1][2]. These particulates are released during the various construction operations, such as loading and unloading activities, earthmoving, transportation of bulk material, exhaust of diesel equipment, storage of materials outdoors, and during the various stages of construction—from the execution of structures, fences, and masonry, to the finishing stage [3][4][5][6].

According to Sa'adeh et al. [7], the effects of construction on the atmosphere are distressing and more apparent in urban areas. Despite the significant impacts caused, there is still a lack of scientific literature on PM in construction sites, although the number of publications has increased since the middle of the last decade [2]. At the international level, one could highlight the studies published by Chiang and Kuo [8] in Taiwan and Feliciano et al. [9] in Portugal, who investigated the concentration of PM from the activities of construction sites; Li et al. [10] in Singapore and Azarmi et al. [11] in England, who assessed air quality by monitoring in the areas surrounding construction sites; Ahmed and Arocho [12][13] in the United States, who compared the PM concentration produced from two construction systems, i.e., wooden panels (cross-laminated timber, CLT) and steel frames; and Sa'adeh et al. [7] in Jordan, who assessed the impact of construction work on fine particulate matter. In Brazil, Araújo et al. [4] and Moraes et al. [5] evaluated the concentration of PM from the activities of construction sites and identified that the activities of construction release particles of various sizes into the environment.

The mentioned scientific studies focused on the characterization of several factors that contribute to PM pollution from construction sites. However, it was observed that researchers have not been using correlatable monitoring and sampling protocols. The lack of systematized procedures means that more variables are added to an already existing set of multiple factors, making it even more difficult to assess conformities and compare the different scientific works available.

2. Guidelines for Measuring and Monitoring Particulate Matter at Construction Sites

2.1. Selection of Construction Sites and Characterization of the Micro-Region

This guideline aims to guide the characterization of airspace, surroundings, and clearances for carrying out PM monitoring. The recommendations for the selection of the construction site are intended for academic studies, as construction companies can apply these recommendations in their construction sites, independently.

In the selection, construction sites that present less external interference should be considered. It is necessary to characterize the occupation of the surrounding area on a spatial scale of 100 m to identify other construction sites in the vicinity and/or other primary sources of particles (industrial activities, fires, etc.). The proximity of the construction site to sensitive receptors and areas with a highly concentrated population should also be analyzed [14]. Finally, attention should be paid to the proximity of traffic routes and airports, as they enhance the concentration and resuspension of particles [15].

2.2. Equipment and Filter Selection

This guideline aims to make recommendations on the selection of equipment and filters to meet the objectives of monitoring, as detailed in **Table 1** and **Table 2**.

Table 1. Equipment and techniques for gravimetric monitoring PM [16].

Equipment	Advantages	Disadvantages	Applications
Gravimetric sampler using filters	This is a sampler that monitors the TSP, PM_{10}, and $PM_{2.5}$ fractions using a suction pump; They usually provide average concentrations over 24 h and require laboratory determination to identify the mass of the filters; The concentrations obtained can be associated with air quality limit values; Reference methods for monitoring suspended particles are based on gravimetric samplers.	High operating costs; Care must be taken with the selection, storage, handling, and weighing of the filters; Results not available in real time.	It is unlikely to be applicable in most situations, as there are delays between the sampling period and the availability of results; Although some types of samplers are small and battery-powered, they do not provide real-time information.

Table 2. Most used types of filters in gravimetric monitors and their characteristics.

Filters	Characteristics	References
Glass fiber filters	Filters that show resistance to high temperatures, low reaction to corrosive material, and high efficiency. They do not break easily with handling, and are recommended for gravimetric processes. They can be used for elementary analysis if their chemical composition is known (typically Al and Si, with large and variable amounts of Na). Recommended by the United States Environmental Protection Agency (EPA).	[17][18]
Polycarbonate filters	Filters that present low thickness, smooth surface, and vitreous aspects. Recommended for performing elementary analysis of the samples, owing to their low blank levels and inertness to gas adsorption. These filters contain carbon, which makes them difficult to use in certain research applications. Widely used in monitoring particulate matter.	[18][19][20]
Teflon filters	These filters have an irregular, porous, and chemically inert structure. They contain carbon, which makes them difficult to use in certain research. Recommended when characterizing the sampled particles using analytical techniques. Recommended by 40 CFR Part 50—Appendix L and O.	[18][19][20][21][22][23]
Cellulose filters	These are highly hygroscopic filters, not recommended for accurate analysis. They are difficult to handle. These filters are necessary for sampling where there is no possibility of using other filters owing to the chemical equivalence between their compositions and the monitored particles.	[17][24]
Quartz filters	Filters with generally high collection efficiency. They are spectral quality filters, that is, more refined filters, with low contents of organic and inorganic contaminants. Highly recommended for carbon analysis. Recommended when chemical analyses are required.	[17][18][24][25]

One selection criterion can be based on the cost of the equipment and, consequently, a greater or lesser number of sampling stations can be installed, depending on the available resources. Another criterion is to choose, according to the need for more detailed and conclusive analyses, gravimetric samplers, which are more expensive and complex, but which yield samples suitable for carrying out analytical methods [26].

As for the filter media to be used, there is no ideal filter for all gravimetric samplers and individual objectives of sampling and analysis [18][27]. For the most appropriate choice of filters, evaluations are recommended with respect to certain aspects, such as characteristics of the particles to be monitored, equipment flow rate, collection methods, and subsequent analyses (physical and/or chemical) [27]. The filter media can be made of polycarbonate, Teflon, cellulose, quartz fiber, and glass fiber, among other materials [24].

Among the most recommended filters, Teflon and polycarbonate filters are highlighted for monitoring at construction sites, as these filters do not contain silica, which is the most abundant component of the inputs used in construction. However, attention is needed, as these filters contain carbon, which makes it difficult to use them in certain investigations at construction sites. According to Galvão et al. [18], polycarbonate and Teflon filters are highly recommended in cases where elementary characterization of the samples is required.

Instead of gravimetric sampling, one can choose sensors for real-time PM monitoring, which is an alternative with low-cost and high agreement compared to reference monitors [28][29][30]. However, any new real-time air monitors must be previously validated, as Fisher et al. [29] suggested, especially in real scenarios.

Finally, the consolidation of the approaches (hybrid monitoring) can be accomplished, exploring information and details not explored in construction sites from one or another isolated monitoring. However, this last recommendation may lose strength as it raises costs for its consolidation.

2.3. Laboratory Activities Prior to Monitoring

This guideline aims to provide guidance on the proper handling, identification, and packaging of filters in the laboratory.

The filters must be separated and stored in identified Petri dishes, with unique identification for recording information [21]. According to EPA [27] and CFR [21], the equilibrium conditions of the environment must have a temperature between 20 and 23 °C, which does not vary by more than ±2 °C over 24 h, and the relative humidity must be between 30 and 40%, without varying by more than ±5% for 24 h. Before any weighing, the filters must remain in the desiccator with silica in the same environment as the balance, under the conditions mentioned above, for at least 24 h.

The filters must be weighed before and after collection in the field, using a microanalytic balance with a nominal precision of 1 µg. Before inserting the filters in the balance, it is necessary to pass them through a load elimination system where they are electrostatically discharged by means of a static charge neutralizer.

Field blank filters and laboratory blank filters should be considered. These filters are used to control contamination and identify research uncertainties [18][27].

Field blank filters are unsampled filters, which are taken to the sampling locations and returned to the packaging conditions. These filters should not vary by more than 30 µg [27]. If the measurements indicate this variation, the EPA [27] advises that, before automatically invalidating any filters, one should try to find the source of the problem and apply corrective measures, that is, weigh the filters again, weigh the adjustment patterns of the scale again, check the temperature and humidity conditions, or have the scale checked by a technician, among other possibilities.

Laboratory blank filters are unsampled filters used to determine possible contamination during weighing and packaging processes in the laboratory. These filters should not have a variation greater than 15 µg [27]. In cases of such variation, the EPA [27] recommends measures similar to those mentioned above.

All filters must be visually inspected before their initial weighing, and those found to be defective are rejected [27]. The inspection should preferably be carried out against a flat light source, and it is recommended to look mainly for the following defects: holes, loose material that must be removed before weighing the filter, discoloration that may be evidence of contamination, nonuniformity of the filter, and other imperfections [27].

The filters must be handled with vinyl gloves (free of dust) and with the aid of tweezers, always avoiding contact with the sampled area. All material used for PM collection must be previously sanitized with a detergent solution and nitric acid and subsequently with distilled and deionized water [27].

Weighing the filters (µg) must follow two procedures in order to standardize the step and reduce the variability, namely: (1) procedure for the scale and (2) procedure for the filters.

- Procedure for the scale:
  - Check that the scale is clean and remove any filter or object in the surroundings, leaving the environment clean;
  - Check the scale level and adjust if necessary;
  - Switch on the balance and let it stabilize for 3 h;
  - Place the silica gel immediately after turning it on;
  - Try to make the internal adjustment, then weigh and record the reference weight value for the blank of the scale;
  - After 3 h, start weighing.
- Procedure for the filter:
  - Tare the balance;
  - Pass the filter through the load elimination system;
  - Place the filter on the scale;
  - Record the weight after the scale stabilizes;
  - Remove the filter and wait for the balance to return to zero;
  - Repeat the weighing (µg) "n" times, passing the filter through the load elimination system again until, in two consecutive measurements, there is variation only in the sixth decimal place (i.e., 0.00000Y, 0.00000X). In this way, the average filter mass in µg is obtained according to Section 5.6.

2.4. Field Monitoring

This guideline aims to provide guidance in the parameter selection for field monitoring, namely, the positioning of equipment, choice of monitoring periods, identification of the most polluting activity phases, identification of applied control measures, identification of the influence of environmental variables, and finally, identification of the annoyance generated and perceived.

2.4.1. Monitoring of Suspended Particles

This monitoring aims to measure and characterize the concentration and chemical composition of particles (TSP, PM_{10}, $PM_{2.5}$, and PM_1) in the different phases of the work (earthworks and foundations phase, structure, fences, and masonry phase, and finishing phase). Although PM_1 is commonly investigated as part of $PM_{2.5}$ and sometimes $PM_{2.5}$ as part of PM_{10}, it is important to investigate them separately. Smaller particles have different characteristics than larger ones, i.e., different settlements and distributional characteristics, physicochemical properties, toxicity, emission, impact on human health, health risk, and others [31][28][32][29]. Similarly, this reasoning should be extended to other PM fractions, confirming, therefore, that the more details investigated of the different PM sizes, the more information is reached for more effective monitoring and controls [33][34].

As a recommendation, Chow [35] highlights the importance of dividing field monitoring into daytime and nighttime periods, as, according to the author, the sources, concentrations, and behavior of particles differ during the day and night. It is recommended, therefore, that the gravimetric monitoring of suspended PM be carried out during the period of 24 h per day, and these 24 h are divided into intervals of effective activity at the construction site (5:00 a.m. to 5:00 p.m.; local time) and periods of stopped work (5:00 p.m. to 5:00 a.m.; local time) [11].

The suggested monitoring period is 10 working days and another day off work (Sunday or other holiday) [5]. The latter is used as a reference, being a day without activities at the construction site [5].

It is suggested to measure fixed points for gravimetric monitoring inside the construction site by installing at least two monitoring points, following the prevailing wind direction, and installing the points in favor of and against the wind [36][14]. In addition, the installation of background monitoring stations close to the urban area under evaluation must be considered.

According to the Environment Agency [26], when locating the fixed points for successful measurements, it is necessary to pay attention to the objectives proposed in the research. Therefore, when choosing the location of the equipment, requirements that interfere with the measurement results must be observed: physical barriers, terrain topography, local infrastructure, and safety for storing the equipment. According to EPA criteria [25]:

- The construction site must generally be downwind, and the emitting activities at the construction site must guarantee the period of exposure to prevailing wind conditions and pollution plumes;
- The equipment must be in an open and flat area with structural similarity and absence of proximity to skyscrapers in at least three directional quadrants of the equipment;
- The airflow around the sampler must be free from any obstruction over a range of at least 270°;
- The entrance of the equipment must be at least 2 m from the entrance of any other equipment;
- For samplers rented for simultaneous sampling (comparative evaluations), the entries must be, at most, 4 m from each other.

According to the CCME [15], distances must be observed and guaranteed to reduce interference, according to the guidelines below:

- It is recommended to keep heavy activities and other major sources of emission of primary particles, according to the road parameters, a distance/volume of at least 25 m from the main arterial circulation routes;
- Vertical and horizontal barriers (vegetation, trees, buildings, walls, among other obstacles) that can impede the normal wind flow around the sampler or monitoring path must be observed;
- The sampler must be at least 90% of the monitoring path, with free airflow, and be away from vertical obstacles, so that the distance between the capture point is at least twice the maximum height of the obstacle, above the sampler path;
- The equipment must be at least 2 m away from any obstacle; it is noteworthy that the fence of the construction site can be a restriction on installation; in this case, it is recommended to position it above the siding;
- The sampler must be at least 20 m away from trees, buildings, or other major obstacles;
- The height of the stations must be at least 2 m above the ground or the height of the breathing zone.

In turn, a location-based monitoring method is suggested for an approach that reinforces the accuracy of measured PM distributional characteristics in their real configurations on construction sites. The real-time PM monitors must be installed from horizontal and vertical distances defined from closer to the investigation sources, with careful investigations of the coexisting activities in the surroundings [32][33].

Attention is needed when locating the sensors in outdoor environments for success regarding the objectives proposed in this type of monitoring. According to Han et al. [34], it is challenging to accurately characterize personal PM exposure in outdoor environments because of the resources required to build and maintain an adequately dense network.

In addition, Venkatram et al. [37] highlight the need for investigation considering meteorological parameters, namely turbulence, direction, and wind speed in the surroundings of monitored sources. Han et al. [34] highlight the importance of investigating the effects of relative humidity in the face of monitoring (and monitors) and its results.

It is necessary to consider that, during environmental monitoring at a construction site with routine works, it is not easy to monitor a specific activity since the various activities are carried out in parallel using different materials and different sizes. For this reason, there is a need for more studies to clarify existing doubts in real configurations by monitoring with low-cost sensors (price below 2000 USD).

Finally, the GLA [14] points to the importance of evaluating the PM throughout the progress of the work in order to monitor the main phases of the work:

- Demolition Phase: characterized by a need to demolish buildings that will not be maintained on the ground;
- Earthworks and Foundations Phase: characterized by a wide-open area at the construction site;
- Structures, Fences, and Masonry Phase: characterized by the elevation of the building with emissions at and above ground level;
- Finishing Phase: characterized by final activities in external and internal environments.

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