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FIELD EVALUATION OF PM_{10} DETECTORS IN A QUARRY ENVIRONMENT

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ABSTRACT

This study is aimed to test and compare two different devices and methods to assess PM_{10} concentration at workplace. An analysis of data collected by Public Administration database on the main nuisance factors at workplaces revealed that in quarrying activities, PM_{10} concentration and airborne dust, in general, represent one of the most relevant hazards. Therefore, to provide a useful stress test for sampling devices, the location selected was a basalt quarry near Rome. Airborne dust tends to be unavoidable in quarries, as this industry necessarily causes ground disturbance. Drilling, blasting, loading, hauling, moving, crushing and screening rocks, as well as transporting the final product away from the quarry, are all dusty activities.

To investigate this phenomenon, we carried out many outdoor sampling campaigns under various meteorological conditions during the period of 2012–2013. In each of them, two simultaneous samples were taken to assess PM_{10} airborne concentration: from one hand, a traditional device for long-term sampling (gravimetric analysis) was employed, while on the other one, a photometric aerosol detection technology developed with a real-time dust monitor was tested. The comparison of collected data revealed that optical readings, if not supported with a specific calibration against physical properties of the dust being measured, may overestimate PM_{10} concentration. In the second period of sampling campaign (2013), the calibration was realized taking into account particle size distribution and density and the samples were collected again. The following analysis showed an improvement in the correlation factor R^2 by more than 20%. This result demonstrates that photometric aerosol detection technology using a nephelometer should be considered suitable for monitoring PM_{10} in dusty workplaces such as quarries or mines, especially when supported by a gravimetric sample to calibrate the optical device itself. This integrated approach seems to be the best option to reduce sampling time without reducing accuracy responses.

Keywords: airborne dust assessment, gravimetric sampler, occupational health and safety, PM_{10} detectors, quarries and mining activities, real-time dust monitor.

1 INTRODUCTION

Quarrying activities, such as drilling, blasting or crushing rock, result in ground disturbance, and fugitive dust from mining surfaces is one of the most important air pollutants. The management of a quarry site must prove that there are compliants with certain legal requirements, among which two of the most common are environmental air protection and workers' safety regarding exposure to airborne particulates [1–3].

For these reasons, in quarries and mines, airborne dust monitoring is, generally, a routine activity.

However, compliance monitoring is not always the only target of sampling strategies. Other goals may include engineering efficacy control, and reactive or proactive approaches.

In general, the choice of airborne particulate sampling method is strictly linked to the purpose of the measurements, which may be a long-term survey of air quality standards [4,5], or rather a short-term analysis to investigate spatial variation (e.g. Ukpebor *et al*. [6] and Alfaro Degan *et al*. [7,8], Gomiscek *et al*. [9]) or the occurrence of peak emissions. Another important application with regard to health and safety: an assessment of the daily or weekly amount of airborne particulate is the final goal of a risk analysis process aimed at quantifying the workers' exposure [10,11].

As introduced, sampling method may be chosen according to two main options: from one side, a traditional gravimetric sampling method, whereas on the other one, a real-time detector generally based on photometric principles.

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Gravimetric samplers use sampling pumps that collect air into a previously weighed filter at a fixed flow rate depending on the target fraction and the standard adopted. If the target is a particulate fraction, a specific sampling head will be installed (PM_{10}, $PM_{2.5}$ being the most common). Each filter is weighed before and after sampling with a precision balance. The difference between the readings allows an assessment to be made of the amount of dust collected on the filter itself and consequently to assess its airborne concentration.

The second option is the use of real-time detectors, the most common being the photometer. Such detectors are based on the optical properties of the particulates and operate by illuminating airborne dust collected in a defined volume. Some of the light beam incident on the particles is reflected, while some is diffracted, and some is refracted. Collectively, these components are referred to as scattered light. The device has an internal sensor detecting scattered light that also generates a current pulse proportional to the light, which is scattered. The intensity of the beam scattered by the particle depends on many parameters, the most important of which being particle size and distribution, density and refractive index [12–14]. Therefore, after the calibration phase developed for the specified dust test, the concentration may be assessed for spherical particles of a known refractive index, density and mean particle dimension.

This case study is aimed at testing these two sampling devices in a workplace environment in which dust concentration is generally high, such as the quarry examined here. It also utilizes an approach in which few gravimetric samples are necessary to calibrate the photometer, thus reducing sampling time without affecting accuracy. To this end, following a preliminary sampling phase, as well as a presentation of the respective measurements and results, a comparative analysis is discussed. The final step then consists in a more accurate investigation of the physical characteristics of the dust being sampled to achieve an integrated calibration. In this stage, a second campaign was realized in which the device was calibrated while taking into account the field results from the gravimetric samples. A good degree of improvement in sampling accuracy was noticed, together with a considerable reduction in sampling time.

2 MATERIALS AND METHODS

2.1 Site description

The site of the field study is a basalt quarry, near Rome, in Italy. The quarry was founded in the early twentieth century to provide basalt ballast for Rome-Ostia railway line. Nowadays, the same material continues to be extracted to supply ballast for the B1 subway line in Rome.

The quarry operates a single 8-h shift per day, 5 days a week. Basalt is drilled and blasted and the shot rock is loaded onto haul trucks by front-end loaders and transported to the primary and secondary crushing plants where it is crushed and sized. The material is then conveyed to the final crushing and screening plants for further processing and stockpiling.

Figure 1: A view of the quarry.

Figure 2: Sampling station locations.

It is well known that most of the quarrying activities mentioned above are classified as dust producing: drilling, blasting, loading and hauling materials, crushing, screening and conveying quarry materials implies impact on air quality and pollutant emission [15–17].

In accordance with the typical geographical sources of dust in quarries [18], four monitoring stations were selected to best characterize the whole quarry plant in measuring airborne dust concentration. These four stations (A–D) were positioned at various key points in the quarry; beside the drilling and blasting area, the primary crushing plant, the secondary crushing plant and the access road, respectively, as shown in Fig. 2.

2.2 Research program and equipment

The entire monitoring program was developed by means of the synergic contributions of two research groups: The Safety and Environment Laboratory and The Applied Physics Laboratory from The Department of Industrial and Mechanical Engineering of Roma Tre University.

The duration of the entire sampling phase was 14 months, from May 2012 to June 2013, and may be described as follows.

In the first stage of the sampling program, carried out in May 2012, the four different sites in the quarry area were surveyed by means of three different campaigns providing a total of 12 measurements (each measurement included both gravimetric and photometric data).

After collecting the data from these three campaigns, a comparative analysis was performed to test devices characteristics [19–22].

As a further step towards a comparative evaluation, the second stage of the research analyzed the chemical and physical characteristics of the dust collected. This step was aimed to better fit the characteristics of the photometer with those of the basalt dust from the quarry. In fact, as demonstrated by Alfaro Degan *et al*. [23], specific calibration of the optical device [24] in relation to the dust being measured may reduce the bias between the two sets of values. The central part of this step was, therefore, that of comparing the dimensional characteristics of A1 Arizona Road dust (used in the factory calibration of the photometer) with the data from the dust collected in the case study.

Calibration was then carried out by modifying some of the parameters of the sampling device, and, in the late spring of 2013, a second set of sampling campaigns was performed.

In this case, the sampling program consisted in monitoring at the same four locations.

Again each location was surveyed with three different campaigns, giving a total of 12 measurements.

With regard to the sampling devices, two airborne dust samplers were supplied by the Department of Industrial and Mechanical Engineering of University Roma Tre.

The gravimetric sampler consisted in a sampling pump connected to a PM_{10} terminal The flow rate was assessed at 1 m^3/h. A 5-μm pore size PVC filter was equilibrated in a room for balance at 20 ± 1°C and 50% ± 5% RH, and then weighed with analytical balance (Mod. Exacta serie ABT 120-5 DM) with 0.01-mg sensitivity. Each gravimetric sample had a 2-h duration to collect a significant dust mass on the filter, in relation to the selected flow rate.

The light scattering sampler consisted in a Nephelometer (Sensidyne) real-time dust monitor, with a sensitivity from 1 to 10,000 μg/m^3, a resolution of 1 μg and tuned to detect particles of dimensions in the range between 0.1 and 10 μm. As described above, the measurements were carried out according to the light scattering method, and the sampler was factory calibrated by comparing the instrument response to the respirable fraction of the International Organization for Standardization (ISO) 12103-1 A_1 Arizona Test Dust, using the gravimetric method NIOSH 0600.

2.3 Methodology

With regard to the gravimetric technique, each filter was weighted using an analytical balance with a precision of 10 μg, including field blanks. The weight of each post sampling filter was recorded besides its corresponding tare weight. The concentration was finally assessed according to the NIOSH 0600 Standard as follows:

$$C = \frac{(W_2 - W_1) - (B_2 - B_1)}{V} \tag{1}$$

where C is expressed in μg/m^3, W_1 is the tare weight of filter before sampling (μg), W_2 is the post-sampling weight of filter (μg), B_1 is the mean tare weight of blank filters (μg), B_2 is the mean post sampling weight of blank filters (μg), and V is the volume as sampled at the nominal flow rate (m^3).

With regard to photometric readings, the concentration displayed was the 2-h weighted average concentration throughout the sampling period. Both minimum and maximum concentrations were recorded over the period in order to check for possible interferences.

The measurements were carried out according to the following relationship:

$$C = \frac{\sum_i R_i N_i}{V} \tag{2}$$

where C is expressed in (μg/m^3), N_i is the particle count in the ith-dimensional range (n), V is the sampled air volume (m^3) and R_i is the calibration parameter (μg) of the ith dimensional range. It is factory calibrated and a function of particle characteristics introduced to assess dust concentration from particle count.

Figure 3: The sampling station in the access road.

In particular, as for spherical particles it will be:

$$R_i = \rho_d \frac{\pi d_i^3}{6} \tag{3}$$

where R_i is expressed in (μg), ρ_d is the airborne dust density (kg/m^3) and d_i is the average mass mean diameter (μm).

Moreover, the particle number for the selected dimensional range is calculated according to the Rayleigh scattering equation:

$$I = \frac{KNV^2}{d^2 \lambda^4} I_0 \tag{4}$$

in which N is the number of detected particles, V is the single particle volume (μm^3), λ is the wave length of laser light (μm), I is the intensity of light scattered by a single particle (W), I_0 the intensity of incident beam (W) and K is a constant factor, which depends on the scattering angle and refractive index of the particle.

Thus, eqn (4) may be expressed more compactly as

$$N = K'I \tag{5}$$

and introducing a further constant K″, airborne concentration assessment may be summarized as follows:

$$C = K'' \rho d^3 N(I) \tag{6}$$

in which the influence on concentration readings of both mean mass average diameter and density are clearly identified.

3 RESULTS

3.1 Data presentation of the first sampling campaign

All the data from the measurements in the first sampling phase (summer 2012) are given in the following tables below (Tables 1–3).

The location codes, respectively, correspond to the drilling area (A), the primary crushing plant (B), the secondary crushing plant (C) and the access road (D) as shown in Fig. 2.

Then simultaneous measurements at each location were compared as shown in Table 3.

The comparative analysis was carried out according to the correlation between the two sets of values. To this aim, a Pearson product–moment correlation coefficient (PPMCC) was calculated

Table 1: Gravimetric samples at each location.

Location (code)	No. of samples	Samples (μg/m^3) # 1	# 2	# 3	Avg. concentration (μg/m^3)	Standard deviation (μg/m^3)
A	3	4390	5890	6310	5530	824
B	3	4790	4030	3850	4223	407
C	3	5720	4230	4870	4940	610
D	3	3670	3530	5010	4070	667

Table 2: Photometric samples.

Location (code)	No. of samples	Samples (μg/m³)			Avg. concentration (μg/m³)	Standard deviation (μg/m³)
		# 1	# 2	# 3		
A	3	5010	5960	6730	5900	703
B	3	4460	4380	4800	4546	182
C	3	6310	5730	5030	5690	523
D	3	4550	3250	5980	4593	1114

Table 3: Differences between simultaneous measurements at each sampling location.

Location (code)	Gravimetric samples, avg conc. (μg/m³)	Optical samples, avg conc. (μg/m³)	Difference (μg/m³)
A	5530	5900	370
B	4223	4546	323
C	4940	5690	750
D	4070	4593	523
Mean value	4690	5182	492

Table 4: ISO 12103-1, A1 ultrafine test dust – particle size distribution by volume.

Particle size (*μm*)	% Less than
1	1.0–3.0
2	9.0–13.0
3	21.0–27.0
4	36.0–44.0
5	56.0–64.0
7	83.0–88.0
10	97.0–100
20	100

together with a linear regression. The scatterplot in Fig. 4 shows the output of this comparison in which the solid line represents a 1:1 relationship.

As shown in Fig. 4, although the photometric response and gravimetric PM_{10} concentration display a linear relationship, the reading is generally higher when recorded with the photometer.

To investigate this response, the calibration method of the photometer itself was examined: the device was factory calibrated using the standard gravimetric method (ISO) 12103-1, A1 Arizona Road Dust.

The standard particle distribution is shown in Table 4.

As previously discussed in eqn (3), dust density is another important physical parameter in the calibration of photometers. With regard to the calibration of the photometer used in this research, the dust density was set at 2.65 g/cm³.

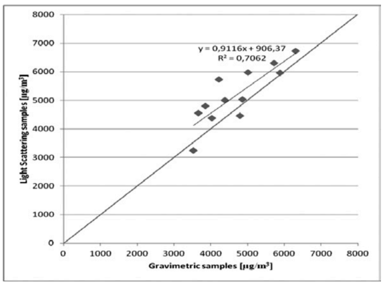

Figure 4: Comparison of photometric response (*Y* axis) with gravimetric concentration (*X* axis) both expressed in µg/m³.

Table 5: The mean ratio of gravimetric to photometric values at each location.

Sample code	$\boldsymbol{\mu}_i$	Sample code	$\boldsymbol{\mu}_i$
A_1	0.87	C_1	0.90
A_2	0.98	C_2	0.73
A_3	0.93	C_3	0.96
B_1	1.07	D_1	0.80
B_2	0.92	D_2	1.08
B_3	0.80	D_3	0.83

Some samples of collected dust were analyzed. The particle size distribution was assessed according to ASTM D422 standard and the average mean mass diameter was 4.3 μm.

Moreover, in accordance with the ASTM D 854 that covers the determination of the specific gravity of soil solids by means of a water pycnometer, the dust was analyzed and found to be 2.79 g/cm³.

Therefore, if the mean mass diameter of the dust test exceeded that of the basalt, the density values were 2.65 and 2.79 g/cm³, respectively. This result suggested that a further adjustment was required, which was realized in two steps. First of all, the mean ratio of the photometric to gravimetric measurement was carried out as follows:

$$\mu = \frac{\sum_i \mu_i}{N} = \frac{\sum_i \frac{D_i}{Ri}}{N} \tag{7}$$

where N is the number of sampled locations, and D_i and R_i are, respectively, the gravimetric and optical measurements taken at the same location (**µg/m**³).

The mean value of $\boldsymbol{\mu}$ was assessed according to eqn (7) and was found to be 0.91. This was assigned to a new pollutant profile in the photometer database called basalt dust.

This value was also compared with the experimental ratio (E_r) defined as follows:

$$E_R = \frac{\rho_d d_d^3}{\rho_t d_t^3} \tag{8}$$

in which ρd is the density of dust being measured, ρt is the density of calibration dust test.

d_d and d_t are, respectively, mean mass diameters of the dust being measured and the calibration test dust, respectively.

Table 6: Gravimetric samples.

Location (code)	No. of samples	Samples (μg/m³) # 1	# 2	# 3	Avg. concentration (μg/m³)	Standard deviation (μg/m³)
A	3	3710	2960	3250	3306	308
B	3	4020	3970	3360	3783	300
C	3	4280	2850	3160	3430	614
D	3	3690	2920	3430	3346	319

Table 7: Optical samples.

Location (code)	No. of samples	Samples (μg/m³) # 1	# 2	# 3	Avg. concentration (μg/m³)	Standard deviation (μg/m³)
A	3	3590	3030	3320	3313	228
B	3	4160	4210	3430	3933	356
C	3	4480	3110	3280	3623	609
D	3	3880	3030	3610	3506	354

Table 8: Differences at each location.

Location (code)	Gravimetric samples, avg conc. (μg/m³)	Optical samples, avg conc. (μg/m³)	Difference (μg/m³)
A	3306	3313	7
B	3783	3933	150
C	3430	3623	193
D	3346	3506	160
Mean value	3466	3593	128

In the case presented here, though densities are 2.65 (test dust) and 2.79 (basalt dust) g/cm^3, respectively, it should be noted that the test dust has a greater mean diameter. With regard to the three samples analyzed, a mean value of 4.3 μm (basalt dust) was found while the mean diameter of the test dust is quoted as being 4.5–5 μm. Therefore, the defined ratio was less than 1 in each case.

The following summer (2013), another sampling campaign was carried out.

The sampling program consisted in monitoring the same four locations, each of which was studied with three different campaigns giving a total of 12 measurements. The sampling duration was kept at 2 h for each measurement to collect comparable data and the measurements were carried out concurrently. The results are presented in Tables 6–8.

As before, the responses were plotted on a scatterplot (see Fig. 5) together with the R^2 value. The solid line represents the 1:1 relationship.

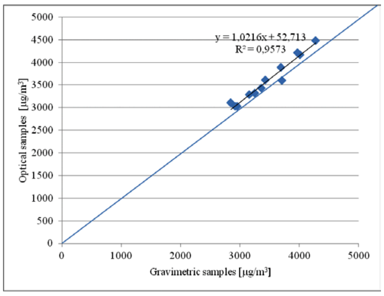

Figure 5: Comparison of photometric response (*Y* axis) with gravimetric concentration (*X* axis) both expressed in µg/m^3.

4 DISCUSSION

The comparison between the two sets of sampled values in the first campaign suggests some considerations: first that the laser light scattering device overestimates the airborne dust concentration when assessed according to the NIOSH 0600 standard. In particular, the mean value of the optical device readings is higher than the mean of the gravimetric readings by a factor of between 10% and 15%. Moreover, the responses of the real-time sampler did not show a strong correlation. This may be seen in Fig. 4 in which the scattered values are observed to have a correlation factor of 0.70.

The readings agreed much more closely after calibration, as shown in Fig. 5 in which the correlation factor was 0.95. Nevertheless, the optical readings were still a little higher than the gravimetric ones except at Location A (sample #1). This response seems to confirm that the main cause of overestimation may be due to the differences in size and density between the particulate of the airborne dust and that of the dust in the A1 test. With regard to density, values are, respectively, 2.65 g/cm^3 for the test dust and 2.79 g/cm^3 for measured dust, whereas the average mass diameter values are 4.5–5 µm (test dust) and 4.3 µm (basalt dust), respectively. Considering eqn (6), and remembering that the efficiency of the optical particle detection system was not tested, and consequently neither was the N(I) parameter, these data would seem to be the main cause of the overestimation. In fact, the calibration factor, assessed by comparing the two sets of values, was found to be 0.91 and, the 'experimental ratio' between the basalt dust and the test dust was <1.

Another important feature to be discussed is the equation of the linear regression before the calibration was carried out. The value of the *Y* axis at the point intersection with the regression line seems to represent a systematic error in the optical readings. This effect is not observed in the second campaign after calibration has been carried out. One possible reason for this may be due to the non-linearity of photometric responses when concentration levels are higher. On comparing the bottom lines of Tables 3 and 8, we notice a reduction in airborne particulate concentration in the second campaign by a factor of 30%. Although dependant on both meteorological conditions and the nature of the quarry activities (it should be borne in mind that the second campaign was carried out a year later), these values do seem to suggest that the higher the dust level is, the lower the correlation factor is. In this regard, it should also be emphasized that the quarry environment represents a major stress test for the device itself whose detection limit is 10,000 µg/m^3.

However, although the concentration values were closer, the photometric readings were still higher than the gravimetric readings by a factor of between 3% and 5%, even when the photometer was calibrated for the particulate being measured. This phenomenon requires further investigation. One possible factor contributing to the overestimation when using the optical device may be linked to its sensitivity. The nephelometer detects particles by measuring the amount of light they scatter.

The intensity of the light scattered depends predominantly on the particle size and shape [25], as well as on the refractive index and colour [26]. As many authors have previously discussed (e.g. Lehocky and Williams [27] and Thorpe and Walsh [28]), the intensity of the scattered light is greater for small particles sized in the range of 0.1–10 μm. This characteristic implies that in the absence of a preliminary size selection, the signal from small particles is dominant, thus producing a bias in the measurements. Although the use of a narrow forward scattering angle reduces this effect, the particle size of airborne quarry dust may match these characteristics. Moreover, higher readings from the optical device may also be caused by atmospheric conditions. Another cause may relate to the efficiency of the inlet of the device. The optical device has a sampling pump that draws air into an inlet, through a length of tubing, and finally into the detector. The device is factory calibrated by comparing the time-weighted average photometer readings with gravimetric samples under indoor conditions. Without a preliminary size selection or a pre-classification of particles, air movement may cause the introduction of particles larger than 10 μm into the sensing detector and thus produce a bias in the reading. This effect may well increase with ambient air velocity, which would seem to match an outdoor environment such as the quarry in our research.

CONCLUSION

This research examined a comparative performance test of two different PM_{10} detectors under the particular conditions found in a quarry environment. The response of the optical device was linearly related to that of the gravimetric sampler, and this result was observed in both campaigns under various particulate concentrations. Moreover, the optical readings were observed to be generally higher than the gravimetric ones. In particular, the optical responses collected in the first campaign were found to be higher than gravimetric responses by a factor of 10–15%, varying according to the sampling location. A considerable reduction of between 3% and 5% (depending on the physical properties of the particle being measured) was observed at the same locations between the sets of values before calibrating the optical device and those measured afterwards.

The research presented here focused especially on particulate size and density. On performing a linear fit to the collected data, the correlation factor between the gravimetrical set of values and optical set increased from 0.70 to 0.95 following calibration. This result indicates a promising improvement and appears to confirm the need for gravimetrical calibration before carrying out sampling, when particle characteristics are different from those of the test dust.

Although these results do not imply that optical devices should substitute gravimetric ones, an optical device does, however, represent a useful, fast, simple tool with which to assess airborne dust concentration providing it is supported by a gravimetric method for its calibration.

Further research is required to improve the calibration procedure of optical devices, to address not only the physical aspects of particles but also their optical properties.

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