DEVELOPMENT OF A METHODOLOGY FOR ASSESSING RESPIRABLE CRYSTALLINE SILICA AND DUST EMISSIONS ASSOCIATED WITH THE DRY MACHINING OF CERAMIC TILES

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1. ABSTRACT

The International Agency for Research on Cancer (IARC) classifies respirable crystalline silica (RCS) in the form of quartz and cristobalite as carcinogenic to humans (group 1). In this regard, the European Union has recently included "Work involving exposure to respirable crystalline silica dust generated by a work process" as a carcinogen in the Directive regulating exposure to carcinogens or mutagens at work (Directive 2019/983, amending Directive 2004/37/EC). For this reason, companies where there are workplaces exposed to RCS must take the necessary measures to minimise worker exposure, using all available technical resources and implementing the most stringent protective measures when RCS is being handled or manipulated.

In regard to handling powder materials, standardised tests are available to assess the tendency of such materials to emit dust when handled (dust emission factor). However, no equivalent methodology exists for ready-formed products to assess emissions associated with dry machining under controlled and standardised conditions.

Consequently, as the available information indicates that activities that include ceramic tile cutting and grinding operations are potential sources of RCS emissions, this study has developed a procedure to assess respirable dust and RCS emissions associated with the machining of ceramic products.

The system developed consists of a wind tunnel, the design and construction of which is based on EN standard 1093 "Safety of machinery. Assessment of the emission of airborne hazardous substances", an automated cutting tool, and a continuous sampling line. Specifically, the system enables continuous measurement of inhalable, thoracic, respirable dust and nanoparticles, as well as collection of samples for subsequent off-line analyses, which include chemical, mineralogical, morphological and toxicological analyses.

Additionally, the results obtained enable the emission rates of respirable dust and RCS to be determined.

A further advantage of this new development is that it makes it possible to quantify preventive and/or corrective measure efficiency.

The results obtained from the tests are considered to be a significant means of obtaining relevant information on workers' potential exposure while machining ceramic products. It should be noted that these test conditions are not representative of the entire range of industrial scenarios in which cutting operations are performed. However, carrying out the operation in a standardised wind tunnel, using an automated tool and under controlled test conditions, guarantees the test's replicability, thus making it possible to compare products and to evaluate the reduction achieved when different preventive and/or corrective measures are implemented.

2. INTRODUCTION

Silicosis caused by exposure to respirable crystalline silica (RCS) has been well known since ancient times. Furthermore, RCS exposure has been associated with the development of lung cancer. In fact, in 1997, the IARC (International Agency for Research on Cancer) concluded that crystalline silica inhaled in the workplace could cause lung cancer in humans [1], a classification that was ratified in 2012 [2]. In this regard, Directive (EU) 2017/2398 included as a carcinogen "Work involving exposure to respirable crystalline silica dust generated in a work process". This European Directive was transposed into Spanish law by Royal Decree 1154/2020 on the protection of workers against risks related to exposure to carcinogens at work, including work involving exposure to RCS as a carcinogen. In addition, Royal Decree 257/2018 amended the list of occupational diseases to include lung cancer due to inhalation of silica dust (Table 1).

Main activities that can cause silicosis and lung cancer due to exposure to free silica dust
Work in mines, tunnels, quarries, galleries and civil engineering works
Siliceous rock carving and polishing, stonemasonry
Dry crushing, screening, sorting and handling of minerals or rocks
Manufacture of carborundum, glass, porcelain, earthenware and other ceramic products, manufacture and preservation of silica-based refractory bricks
Manufacture and handling of abrasives and washing powders
Demoulding, deburring and sand clearing operations in foundries
Operations involving grinding wheels (for polishing, deburring) that contain free silica
Sandblasting and emery work
Ceramic industry
Iron and steel industry
Manufacture of refractory products
Manufacture of abrasives
Paper industry
Manufacture of paints, plastics and rubber

Tabla 1. *Work activities recognised (RD 257/2018) as able to cause silicosis and lung cancer*

On the basis of the above, it should be noted that it is imperative not only to combat the problems associated with handling and/or processing crystalline silica-containing powdered materials, but also to deal with RCS exposure generated during the manufacture, post-processing and installation of crystalline silica-containing finished goods. In this regard, available information suggests that operations involving machining (cutting, polishing, etc.) of crystalline silica-containing products are potential sources of RCS emissions [3].

3. OBJECTIVES

One parameter of significant interest in order to assess, control and minimise the risks associated with emissions of particulate matter when powdery materials are handled is their dustiness, i.e., their tendency to produce dust when handled. In this respect, standardised methods exist to determine this parameter (EN 15051).

In the case of machining ready-formed products, different methods have been developed to assess emissions associated with machining [4][5][6], including initiatives aimed at certifying machinery [7]. It should be noted that such methods are mostly based on internal procedures that are difficult to replicate. However, the NIOSH (National Institute for Occupational Safety and Health, USA) has developed a system based on standard EN 1093 to assess the silica emissions associated with cutting fibre cement [8], which has recently been used to assess dust and RCS emissions associated with the grinding of natural and artificial stone [9]. The INRS (Institut National de Recherche et de Sécurité, France) and FIOH (Finnish Institute of Occupational Health, FIOH) have also based their work on this standard to develop methodologies for standardised assessment of wood dust emissions generated when cutting and sanding wood products [10][11].

That is why the aim of this study was to develop a test, based on the aforementioned standard (EN 1093 "Safety of machinery. Assessment of the emission of airborne hazardous substances") that would enable the emissions associated with the machining of ceramic tiles to be characterised. Such a test must enable determination, under rigorously controlled and standardised conditions, of the concentration in mass and number of inhalable, thoracic, respirable dust and nanoparticles, as well as making it possible to take samples for subsequent off-line analyses (Figure 1). It is worth noting that, based on available information, such a standardised test would be the first of its kind in the world designed and constructed specifically to assess emissions associated with the machining of ceramic products.

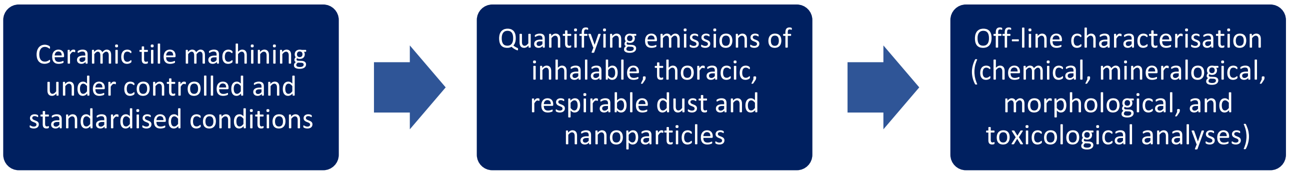


Figura 1. *Aims of this study*

4. METHOD

A wind tunnel based on standard EN 1093 "Safety of machinery. Assessment of the emission of airborne hazardous substances" was designed and built. The wind tunnel consists of a booth in which the actual machining takes place. All generated dust is transferred via an air stream to the sampling duct (Figure 2).

The air flow rate is chosen to ensure that the pollutant under study is transported from the machine to the sampling section. For fine particles and gases (fumes, respirable particles, etc.), the standard indicates that a velocity of 0.1 m/s in the booth section should be sufficient.

Particle sampling needs to be performed isokinetically and the measurement must last long enough to ensure that sufficient sample quantity is collected for subsequent off-line analysis.

The sampling duct needs to be fitted with equipment that allows continuous measurement of the different particle size fractions of relevance to human health (inhalable, thoracic, respirable and nanoparticles), as well as equipment that allows samples to be collected for subsequent off-line analyses, including chemical, morphological, mineralogical and toxicological analyses.

In order to assess the emissions associated with cutting ceramic tiles, an automated cutting machine has been designed, built and placed in the wind tunnel.

Finally, this newly developed system was tested with different ceramic products, thus enabling the system to be validated and the test procedure and data analysis to be defined.

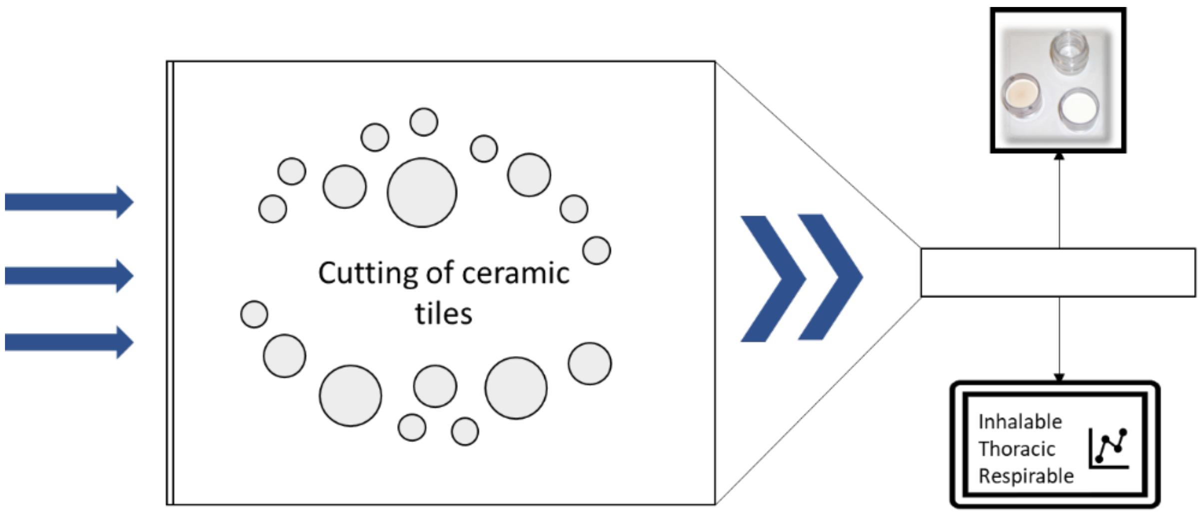


Figure 2. *Diagram of the wind tunnel developed for this research*

5. RESULTS

5.1. WIND TUNNEL CONSTRUCTION

Based on the specifications given in the aforementioned standard (EN 1093), a wind tunnel was built that comprises the following components Figure 3):

- A filter panel at the entrance to the booth;
- A booth in which the cutting operation takes place;
- A booth-to-sampling duct transition zone;
- A sampling duct.

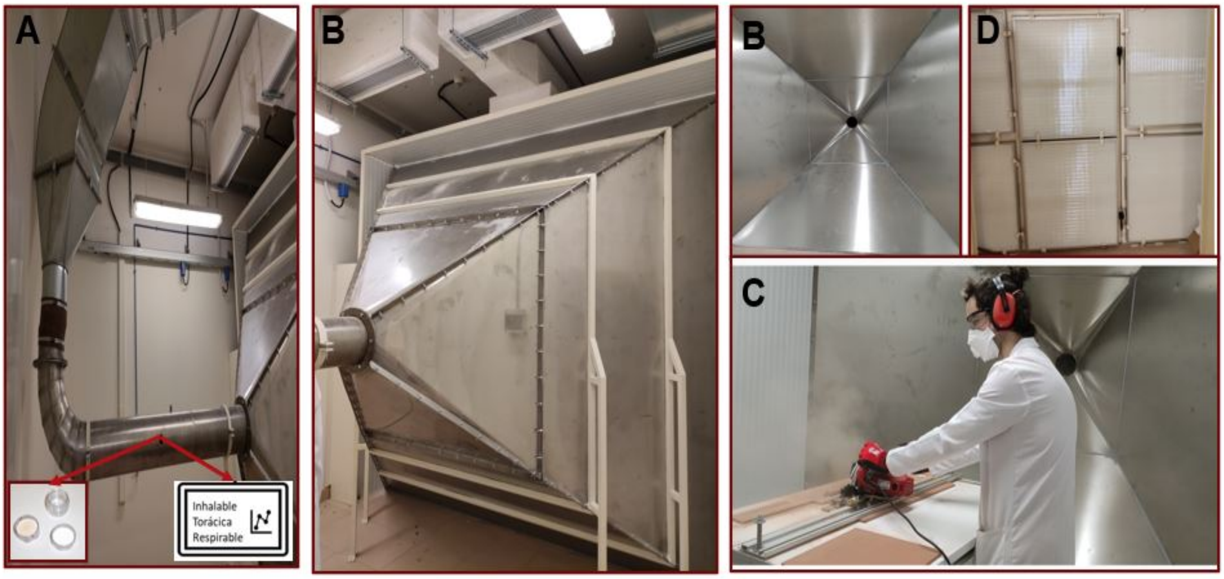


Figure 3. *Wind tunnel components: A) sampling duct, B) transition from booth to sampling duct, C) booth in which cutting is carried out, and D) filter panel at booth entrance.*

5.2. SAMPLING SYSTEM

Since the intention behind taking samples was to be able to characterise emissions of inhalable, thoracic, respirable dust and nanoparticles, as well as to carry out subsequent off-line analyses, a sampling line was developed that basically consists of an isokinetic probe and a flow divider, to which at least one sampling cyclone for the respirable fraction and a continuous particulate matter monitor are connected (Table 2 and Table 3). It is important to realise, given that sampling must be carried out under isokinetic conditions, that different sampling nozzles and an external pump are used to allow the necessary adjustments to be made to ensure proper isokinetics. In addition, equipment for measuring nanoparticle concentrations and/or specific devices for collecting samples for subsequent chemical, mineralogical, morphological or toxicological analyses can be connected.

Device	Characteristics / Operation	Required / Optional
	**Isokinetic probe (Grimm 1152 isokinetic set):** The isokinetic probe has several nozzles that enable sampling under isokinetic conditions.	Required
	**Flow splitter (TSI 3708)** Allows different devices to be connected during the test.	Required
	**Sampling pump (AirChek TOUCH Pump):** In order to ensure proper isokinetics, an external pump is available to adjust sample flow rate.	Required

***Table 2**. Components required to ensure isokinetic sampling and to enable the connection of different sampling devices*

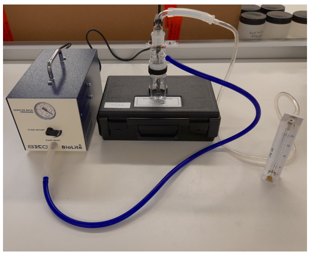
Device	Characteristics / Operation	Required / Optional
	**Cyclone (GK2.69) and sampling pump (AirChek TOUCH Pump)** Separates the respirable fraction, which is collected on a PVC filter for subsequent sample analysis. Respirable crystalline silica is determined from the sample collected on these filters.	**Required**
	**Real-time monitor of micrometre-range particulate matter (Grimm EDM264)** Optical monitor providing real-time concentration of inhalable, thoracic and respirable dust (0.35-35 µm)	**Required**
	**Real-time monitor of micrometre-range particulate matter (ELPI+)** Provides real-time particle number and mass concentration and particle size distribution (6nm-10µm).	**Optional**
	**Biosampler:** A device used to collect a sample for subsequent toxicological analysis.	**Optional**
	**TEM:** A device used to collect samples for subsequent morphological analysis	**Optional**

***Table 3**. Components required to carry out particulate material sampling*

It should be noted that further measuring devices could be connected depending on the specific requirements of each study.

5.3. DESIGN AND CONSTRUCTION OF AN AUTOMATIC CUTTING SYSTEM

In order to guarantee cutting replicability and reproducibility, the cutting tool was automated on the basis of the results obtained (Figure 4). A servomotor and a spindle were installed to enable automatic advance of the tool. Advance speed, On/Off times and cutting length can be adjusted using a PLC system and display.

Figure 4. *Overview of the automatic system (left) and close-up of the servomotor and spindle (top right) and of the display and controls (bottom right).*

5.4. DEVELOPMENT OF THE TEST PROCEDURE AND DATA ANALYSIS

In order to guarantee the representativeness of the results and to collect enough sample for subsequent off-line analyses, the following experimental protocol was defined (Figure 5):

Figure 5*. Diagram of the test procedure described below*

The system includes a continuous monitor that allows for real-time definition of whether additional cuts are required to obtain sufficient sample quantity.

The results obtained provide the following information: concentration of inhalable, thoracic, respirable dust and nanoparticles.

Furthermore, in each replicate, a sampled filter of the respirable fraction is obtained which can then be analysed for RCS content using XRD. In this respect, the filters are analysed according to standard ISO 16258-2:2015 Workplace air - Analysis of respirable crystalline silica by X-ray diffraction - Part 2: Method by indirect analysis.

The filters undergo a redeposition process on a silver membrane (Figure 6). The percentage of crystalline silica in the form of quartz is quantified using a calibration straight line on filters obtained by known additions of a certified standard.

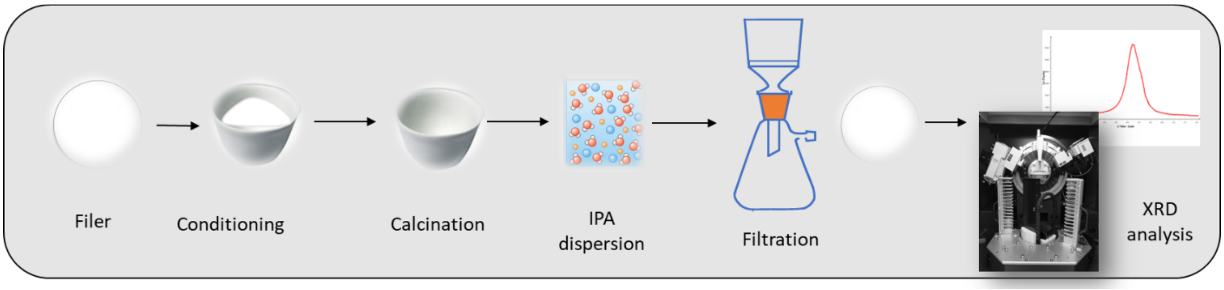


***Figure 6**. Filter analysis procedure to determine the amount of respirable crystalline silica*

Given that the concentration recorded will depend on environmental conditions (air renewal, dimensions, etc.) and on the location of the sampling point, it is important to point out that, in order to normalise the results, an estimate is made of the emission rate (mass of dust and RCS emitted per minute of cutting [E.1] per linear metre of tile cut [E.2] or per gram of tile removed during cutting [E.3]). The parameter will depend on operating variables (tool, advance speed, disc diameter, etc.) and on the product processed, but it will be independent of the environment in which the operation is carried out.

$$EF_{i\_t} = \frac{\bar{c}_i \cdot Q \cdot t_{total}}{t_{active\ cutting}} \text{ [E.1]} \qquad EF_{i\_l} = \frac{\bar{c}_i \cdot Q \cdot t_{total}}{l} \text{ [E.2]} \qquad EF_{i\_m} = \frac{\bar{c}i \cdot Q \cdot t_{total}}{m} \text{ [E.3]}$$

Where:

- EF_{i_t}: Emission factor of dust fraction i expressed in mg dust emitted per minute of active cutting (mg/min)
- EF_{i_l}: Emission factor of dust fraction i expressed in mg dust emitted per linear metre of tile cut (mg/m)
- EF_{i_m}: Emission factor of dust fraction i expressed in mg dust emitted per gram of tile removed during cutting (mg/g)
- c_i: Mean concentration of dust fraction i during the test (mg/m^3)
- Q: Suction flow rate (m^3/min)
- t_{total}: Test duration (min)
- $t_{active\ cutting}$: Time during which cutting is active (min)
- l: Cut length (m)
- m: Mass of tile removed during cutting (g). It is estimated from the thickness and density of the workpiece, thickness of the cutting disc and cut length.

From the silica content on the filters of the respirable fraction, the RCS emission rate can be determined according to equations [E.4], [E.5] and [E.6].

$$EF_{RCS\_t} = \frac{\bar{c}_R \cdot Q \cdot t_{total}}{t_{active\ cutting}} \cdot CS \text{ [E.4]} \qquad EF_{RCS\_l} = \frac{\bar{c}_R \cdot Q \cdot t_{total}}{l} \cdot CS \text{ [E.5]} \qquad EF_{RCS\_m} = \frac{\bar{c}_R \cdot Q \cdot t_{total}}{m} \cdot CS \text{ [E.6]}$$

Where:

- EF_{RCS_t}: RCS emission factor in mg RCS emitted per minute of active cutting (mg/min).
- EF_{RCS_l}: RCS emission factor in mg RCS emitted per linear metre of tile cut (mg/m).
- EF_{RCS_m}: RCS emission factor in mg RCS emitted per gram of tile removed during cutting (mg/m).
- CS: Percentage of crystalline silica in the respirable dust sample collected during the test (%).
- c_R: Mean respirable dust concentration during the test (mg/m^3)
- Q: Suction flow rate (m^3/min)
- t_{total}: Test time (min)
- $t_{active\ cutting}$: Time during which cutting is active (min)
- L: Cut length (m)
- m: Mass of tile removed during cutting (g). It is estimated from the thickness and density of the workpiece, thickness of the cutting disc and cut length.

5.5. ASSESSMENT OF CORRECTIVE MEASURE EFFICIENCY

The method developed allows the efficiency of the implemented corrective measures (suction, wet cutting, etc.) and preventive measures (reduction of the crystalline silica content of a product, etc.) to be assessed.

In order to determine the efficiency of such measures, the test procedure described above is followed and the efficiency of the measure being assessed is calculated from equation [E.7]:

$$Efficiency\ (\%) = \left(1 - \frac{EF_2}{EF_1}\right) \cdot 100 \qquad \text{[E.7]}$$

Where:

- EF_2: Emission factor obtained from the test performed with corrective measures.
- EF_1: Emission factor obtained from the test performed without corrective measures.

5.6. VALIDATION OF THE METHODOLOGY

A variety of ceramic products were cut in order to validate the applicability of the system developed for the study of emissions associated with the cutting of ceramic tiles, and to assess the replicability of the test.

By way of example, Figure 7 (product A) and Figure 8 (product B) show the evolution over time of the inhalable and respirable dust concentrations during two of the tests carried out. Figure 9 shows the evolution over time of nanoparticle concentration during the test with product C.

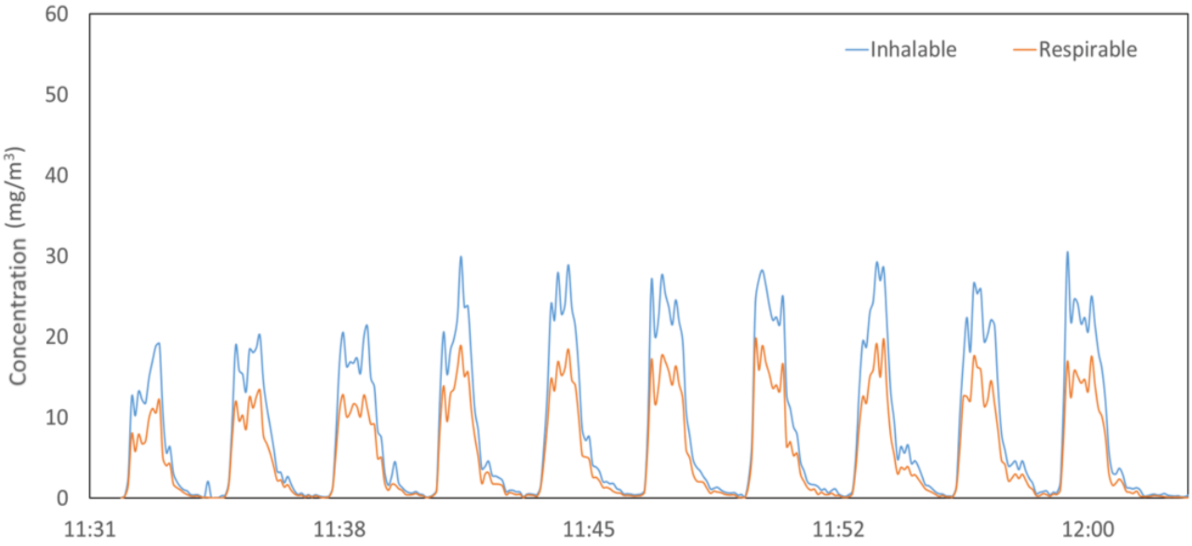


***Figure 7**. Evolution of inhalable and respirable dust concentration during the test with product A.*

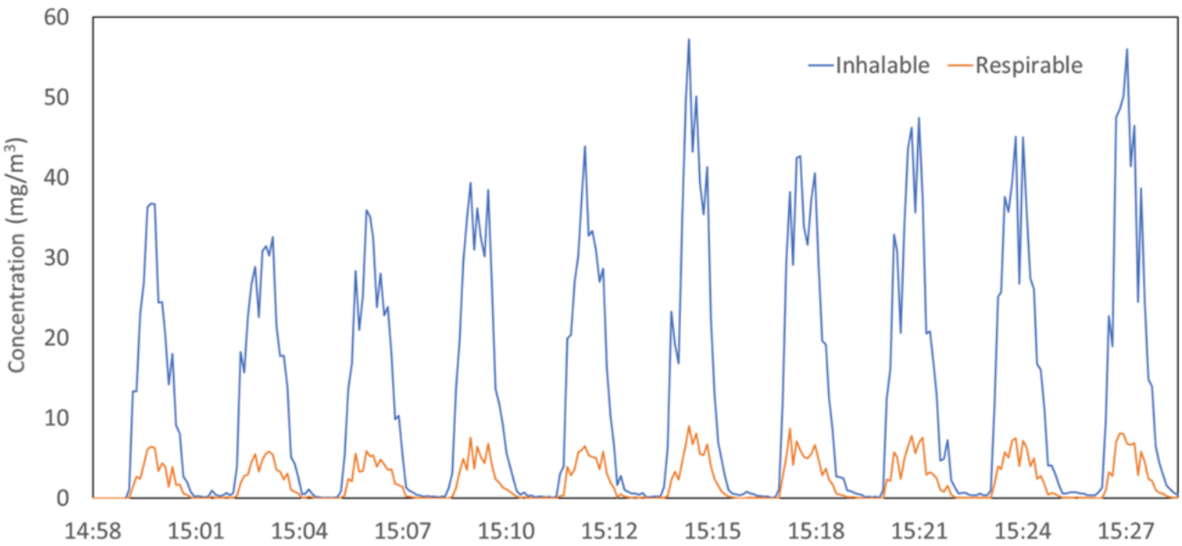


***Figure 8.** Evolution of inhalable and respirable dust concentration during the test with product B*

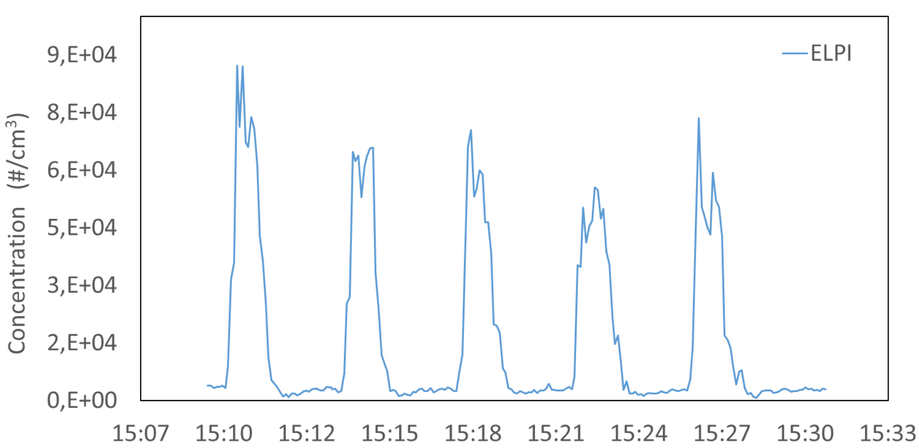


***Figure 9.** Evolution of nanoparticle concentration during the test with product C*

The emission factors can be determined from the experiments by applying the equations described above (Table 4).

	Fraction	FE_{i_t} (mg/min)	EF_{i_l} (mg/m)	EF_{i_m} (mg/g)
Product A	**Inhalable**	1 695	2825	88
	Respirable	1 077	1795	56
	***Nanoparticles**	$6{\cdot}10^{13}$	$1{\cdot}10^{14}$	$3{\cdot}10^{12}$
Product B	**Inhalable**	2 537	4229	131
	Respirable	405	675	21
	***Nanoparticles**	$8{\cdot}10^{12}$	$1{\cdot}10^{13}$	$4{\cdot}10^{11}$
Product C	**Inhalable**	1979	6598	205
	Respirable	275	917	28
	***Nanoparticles**	$3{\cdot}10^{12}$	$9{\cdot}10^{12}$	$3{\cdot}10^{11}$

*The emission factor for nanoparticles is expressed in #/min, #/m and #/g

***Table 4**. Emission factors of inhalable and respirable dust and nanoparticles*

After determining the silica content from the filters according to the method described in Section 5.4, the percentage of crystalline silica present in respirable dust and the respirable crystalline silica emission rate can be determined (Table 5).

Product	EF_{t_SCR} (mg/min)	EF_{l_SCR} (mg/m)	EF_{m_SCR} (mg/g)
A	140	233	7
B	73	122	4
C	58	193	6

***Table 5**. RCS emission factors*

On the other hand, by way of example, Table 6 shows the reduction achieved in one of the experiments performed to assess corrective measure efficiency. These data are given only to show the possible applications of the methodology developed and should not be taken as mean or representative values, as they are based on preliminary results. Efficiency values in suction systems depend on many variables (flow rate, design of the collection system, degree of cutting element enclosure, etc.).

	Without corrective measures	With corrective measures (tool connected to a vacuum cleaner)
EF_{t_R} (mg/min)	748	581
Efficiency (%)	22	

***Table 6.** Assessment of efficiency relating to the implementation of corrective measures*

In addition, as indicated above, the system developed enables the sample to be characterised, e.g., by mineralogical, chemical, morphological and toxicological analyses. As an example, a micrograph and EDX analysis performed by scanning electron microscopy with an energy dispersive detector (SEM-EDX) is shown.

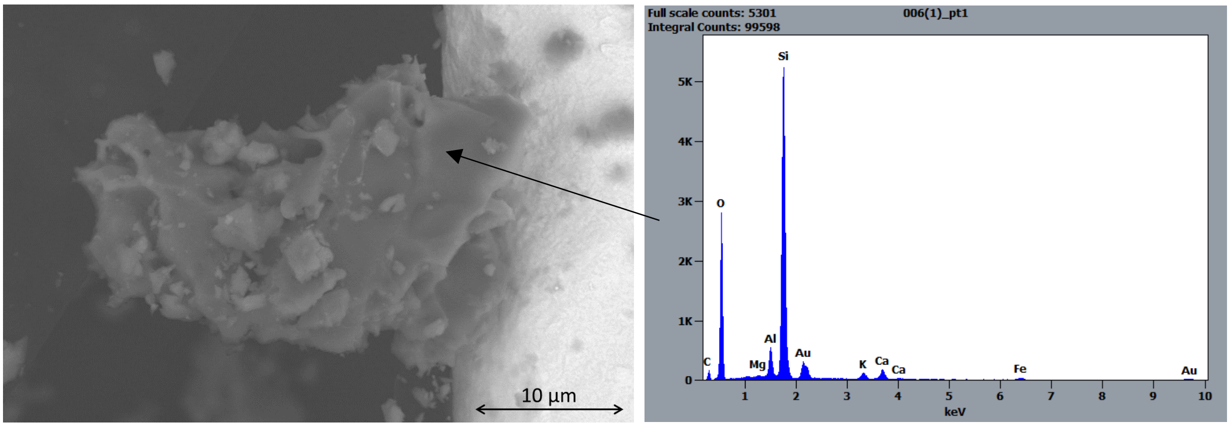


***Figure 10**. SEM image and EDX analysis of the test particle*

CONCLUSIONS

- A standardised wind tunnel was designed and built, along with a method to enable quantification, under standardised conditions, of inhalable, thoracic, respirable dust and nanoparticle emissions in the machining of formed workpieces. It should be noted that this standardised test is the first in the world designed and built specifically to assess the emissions associated with the dry machining of ceramic products.
- The method thus developed enables samples to be collected for subsequent off-line analyses, such as chemical, mineralogical, morphological and toxicological analyses.
- The availability of a standardised methodology is considered to be a highly useful means of comparing the emissions generated when different products are processed, and of assessing implemented preventive and/or corrective measure efficiency.
- However, given the large number of variables (material, cutting elements and corrective measures) and possible industrial scenarios (degree of ventilation and/or enclosure), systematic work is still required to differentiate between the influence of the different variables in order to provide consistent results.

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