Chemical and Biological Hazard Prevention

Studies and Research Projects

REPORT **R-801**

Construction Workers' Crystalline Silica Exposure

Statistical Analysis of a Literature-Based Database

Jean-François Sauvé
Charles Beaudry
Denis Bégin
Chantal Dion
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Jérôme Lavoué

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PEER REVIEW

In compliance with IRSST policy, the research results published in this document have been peer-reviewed.

SUMMARY

Prolonged inhalation exposure to respirable dusts containing crystalline silica is known to cause respiratory diseases, including lung cancer and silicosis. Numerous studies have shown the overexposure of construction workers to crystalline silica, since this compound is present in many materials used on construction sites. The assessment of crystalline silica exposure in this industry is a challenge due to the many working conditions and the temporary nature of the construction sites.

To improve knowledge about the working conditions that can expose construction workers to silica and to respond to an initial request from the CSST, a joint team from the Université de Montréal and the IRSST developed a literature-based database of the levels of occupational exposure to this contaminant. This first project was funded by the IRSST and was the subject of a report published in 2011 by this organization. The database contains more than 10,000 exposure measurements, originating from scientific journals, external databases, and reports from research organizations, collected following an exhaustive review of the literature covering the last 25 years. Descriptive analyses produced from quantitative measurements in the database led to the identification of the occupations and tasks associated with the highest exposures. The researchers nevertheless highlighted the important potential of additional information associated with the use of multivariate analysis techniques, allowing evaluation of the simultaneous influence of several variables on the exposure levels. The present project had the primary objective of extending the analysis of the database in order to refine the crystalline silica exposure profile and to evaluate the contribution of the different exposure determinants.

The crystalline silica exposure data were first selected on the basis of the sampling strategy, resulting in two complementary analyses whose objective was to evaluate exposure levels by occupational title in relation to an occupational exposure limit (OEL) over eight hours, and by task according to their duration of execution. The Monte Carlo method was used to reconstruct the samples originating from data reported in the form of summary parameters (e.g., geometric mean and geometric standard deviation, arithmetic mean, range), allowing their combined analysis with the results reported as single measurements. Statistical models including variables such as occupation, task performed, measurement duration, year and sampling strategy, project type (demolition, new construction and renovation), activity sector (e.g., civil engineering, residential), environment (outdoors, indoors), and control methods were developed and interpreted by multimodel inference. These analyses were also carried out on the respirable dust samples in order to evaluate the presence of potentially different effects of the exposure determinants. Furthermore, by cross-tabulating the crystalline silica and respirable dust data, the differences between the crystalline silica percentages in the airborne samples could be evaluated by occupation, task, tool, material, and source control method.

Crystalline silica data for the purpose of comparison to an OEL were analyzed using 1346 measurements covering 11 occupation categories. The model containing all the variables explained 22% of the variability in the measurements, while the year and sampling strategy (regulatory compliance vs surveillance) were the variables with the most impact on exposure. Increased sampling duration was associated with lower levels, while time trends by strategy went in opposite directions with a reduction of 17% per year (regulatory compliance) compared to an

increase of 9% per year (surveillance). The use of control methods (without consideration of the specific type) reduced the concentrations by 18% outdoors and by 24% indoors. The highest geometric means predicted for the year 1999 for eight hours were found for drillers (0.24 mg/m^3), underground workers (0.22 mg/m^3), roofers working on concrete tile roofing (0.15 mg/m^3), and cement finishers (0.13 mg/m^3). The effects of the determinants for respirable dust, estimated from 1137 measurements, were comparable to those for crystalline silica; however, the agreement between the geometric means predicted for the two types of contaminants was moderate (Spearman correlation coefficient of 0.45).

For the analysis of task-related levels, 1466 crystalline silica measurements divided into 27 task categories were selected. The model containing all the variables explained 60% of the variations in exposure levels, and all the contextual variables were highly predictive. The geometric means predicted for the year 1998, based on the median duration by task, were higher for bush hammering of concrete (0.73 mg/m^3), breaking masonry with multiple tools (including jackhammers/percussion drills) (0.59 mg/m^3), tunnel boring (0.27 mg/m^3), abrasive blasting (0.19 mg/m^3), and brick joint grinding (0.19 mg/m^3). A significant reduction in concentrations was observed with spraying systems (71%) and dust exhaust systems (69%) built into the tools. For respirable dust (1566 measurements), the efficiency rates for the control methods were generally higher, with reductions of 88% and 81% of the exposure for these same categories. The agreement between the predictions for the two contaminants was also higher with a Spearman correlation coefficient of 0.70.

The median percentage of respirable crystalline silica, calculated from 924 samples, was 11%. The majority of the percentages by category of occupation, task, tool, material and source control method were between 6% and 16%, with the highest value (19%) being found for the "sand" material category.

The data analysis showed a generalized overexposure situation with respect to the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) and the Québec standard, indicating a long-term risk of occupational diseases for all of the occupations studied. The results obtained for the evaluation according to the task performed show that this strategy allows a better characterization of the exposure-related factors and a better pinpointing of the intervention priorities to control the crystalline silica exposure levels on construction sites during a work shift.

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ACRONYMS AND ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
BPW	Building and Public Works
CSST	*Commission de la santé et de la sécurité du travail* (Québec Workers' Compensation Board)
ÉDALI	*Exploration des données d'analyse des laboratoires de l'IRSST* (Exploration of IRSST laboratory exposure data)
GM	Geometric mean
GSD	Geometric standard deviation
IMIS	Integrated Management Information System
InVS	*Institut de veille sanitaire*
IRSST	*Institut de recherche Robert-Sauvé en santé et en sécurité du travail*
LD	Limit of detection
Max	Highest value
Min	Lowest value
ND	Not detected
NIOSH	National Institute for Occupational Safety and Health
OEDB	Occupational exposure database
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration
ROHS	Regulation respecting occupational health and safety (Québec)
RSD	Relative standard deviation
SS	Summary statistics
TLV	Threshold Limit Value
TWAEV	Time-weighted average exposure value
WAC	Weighted average concentration

1. INTRODUCTION

1.1 Context

Respiratory health problems resulting from prolonged exposure to mineral dust, particularly in miners, have been known since time immemorial. In addition to increasing the risk of lung cancer [1,2], the inhalation of respirable silica dust can cause silicosis, a type of pulmonary fibrosis. This is one of the oldest recognized occupational diseases. The development of mechanized tools for stoneworking in the 20th century transformed this disease into a widespread occupational health problem [3]. The problem of occupational exposure to silica was the reason for the creation of the first occupational health statutes, and led to the development of means of prevention such as the use of wet processes and ventilation to reduce dust emission at the source [4-6]. The many efforts in the last century to prevent this disease have therefore resulted in an appreciable improvement in working conditions in the most affected industries, particularly mines and quarries. Furthermore, recent studies have made it possible to associate silica exposure with health effects other than those affecting the respiratory system, namely kidney diseases and autoimmune diseases, including rheumatoid polyarthritis, systemic lupus erythematosus, and scleroderma [7].

Nonetheless, crystalline silica exposure remains a current problem. In particular, high exposure levels have been identified by several recent studies in the construction industry [8-11], which employs almost two-thirds of the workers potentially exposed to silica in Québec [12]. The construction industry ranked first in deaths due to silicosis in the United States between 1990 and 1999 [13], and in workers under 45 years of age between 1968 and 2004 [14]. In Québec, there were 19 compensated deaths related to silica exposure in the Building and Public Works (BPW) sector between 1995 and 2009 [15]. Between 40 and 98 cases of silicosis were reported annually between 2006 and 2010[1] province-wide, with all industries combined [17].

The construction industry poses several methodological challenges for analyzing the risk associated with silica exposure. Many tasks are likely to expose workers to crystalline silica since it is one of the main components of several construction materials such as concrete, cement, mortar and asphalt [18-20]. Also, working conditions vary greatly. For example, silica exposure for an unskilled labourer can vary from one day to the next, going from zero to high depending on the tasks performed and the work site. The temporary nature of construction sites and the mobility of the labour force further complicate the evaluation of health risks. Since 2008, the *Commission de la santé et de la sécurité du travail* (CSST) has been applying a "zero tolerance" policy to crystalline silica exposure in the construction industry, a commitment renewed for the year 2012 [21]. The Construction Action Plan is included in the CSST's 2010–2014 Strategic Action Plan [22].

[1] The number of reported cases may include new cases and newly-reported old cases since silicosis has been a reportable disease in Québec since 2003 [16].

1.2 Québec database for occupational silica exposure in the BPW sector (IRSST project 0099-7530)

Crystalline silica exposure levels in the Québec construction industry are generally unknown. A 2007 report by the Montreal Department of Public Health showed levels frequently above the recommendations, based on 120 individual evaluations [10]. The authors emphasized the challenges represented by the significant variability in working conditions and the rarity of data in this economic activity sector. According to the ÉDALI[2] tool recently developed by Lavoué et al. [23], an average of only 10 respirable silica measurements per year have been collected by Québec public network teams since 1985 in the construction field. To improve knowledge about the working conditions that can expose construction workers to silica, and to respond to an initial request from the CSST, a joint team from the Université de Montréal and the IRSST developed a literature-based occupational exposure database (OEDB) for this contaminant. This initial project was funded by the IRSST and was the subject of a report published in 2011 by this organization, which was translated into English [24]. The database[3] contains more than 10,000 exposure measurements covering a 35-year period (1974–2009) taken from scientific journals, external databases, and reports by research organizations. In addition to the public scientific literature, the researchers had access to collections of unpublished data obtained from researchers associated with the United States ACGIH construction committee, and the *Institut national de veille sanitaire* (InVS) in France. Each measurement was associated with information elements allowing their interpretation, namely the tasks performed, the type of material, the tools used, and the means of prevention that were used.

IRSST project 0099-7530 led to the creation of a unique resource of its type internationally for documenting silica exposure in the construction sector. The classical literature review of the methods of prevention led to several avenues of recommendations, and the univariate analyses (considering the effect of each variable independently from the others), carried out from quantitative measurements in the database, identified the occupations and tasks associated with the highest exposures. The researchers nevertheless emphasized the significant potential of additional information associated with the use of multivariate analytical techniques, by which the simultaneous impact of several factors on the exposure levels can be measured. Another development strategy mentioned by the authors was the processing of the data presented in summary form, for example an average of 10 measurements. Refining the descriptive portrait drawn in this first report by using advanced statistical tools was a major recommendation of the authors.

[2] Exploration des Données d'Analyse des Laboratoires de l'IRSST (Exploration of IRSST laboratory exposure data): http://www.irsst.qc.ca/-outil-edali.html

[3] http://www.irsst.qc.ca/-outil-bd-exposition-silice.html

1.3 Objectives

The primary objective of this research activity was to refine the crystalline silica exposure profiles and to estimate the influence of the different determinants of exposure in the construction sector, from measurements in the recently created database. The specific objectives were:

- To estimate the respirable crystalline silica concentrations in relation to occupation for data allowing comparison to an occupational exposure limit;
- To evaluate the respirable crystalline silica concentrations in relation to the task performed, in order to estimate their contributions to the exposure profile over a work shift;
- To quantify the effect of exposure determinants, such as the environment and the construction site characteristics, as well as the reduction in concentrations associated with dust abatement techniques.

While the main interest of the project was focused on respirable crystalline silica exposure, the database also contains respirable dust results, of which a major proportion are associated with the silica measurement performed on the same collected sample. The literature data indicate that the crystalline silica content of the respirable dusts generated by construction activities can be extremely variable [11, 25]; therefore the estimation of crystalline silica concentrations from respirable dust cannot be readily considered. Nevertheless, conclusions regarding the different factors contributing to silica exposure on construction sites could be refined using the information on the determinants associated with the dust measurements. To this end, this project also included the following two specific objectives:

- To quantify the effect of the exposure determinants on the respirable dust concentrations in order to compare them to the respirable crystalline silica results;
- To investigate the variations in crystalline silica percentages according to key exposure determinants, in particular the occupations, tasks, tools and materials.

2. METHODOLOGY

2.1 Preparation of the analytical data database

2.1.1 Selection of the exposure data

The existing database contains more than 6000 lines of information corresponding to 11,845 individual measurements, but had to be limited to the data most relevant to the objectives of the work. To do this, the data were divided into two sub-databases based on the sampling strategy (Figure 1). To evaluate exposure by occupation for one full work shift, an initial sub-database was created from the samples collected for purposes of comparison of the exposure levels to a limit value or regulatory standard. The second sub-database was developed by selecting the measurements that were collected for the purpose of assessing exposure during specific tasks. The two sub-databases thus created were then divided into two, based on the nature of the contaminant sampled, with one containing respirable crystalline silica (excluding cristobalite) measurements and the other containing respirable dust measurements. The respirable cristobalite results were not retained in our analyses due to the small number of measurements and the different exposure limit values in the *Regulation respecting occupational health and safety* (ROHS), namely 0.05 mg/m^3, compared to 0.1 mg/m^3 for respirable quartz [26].

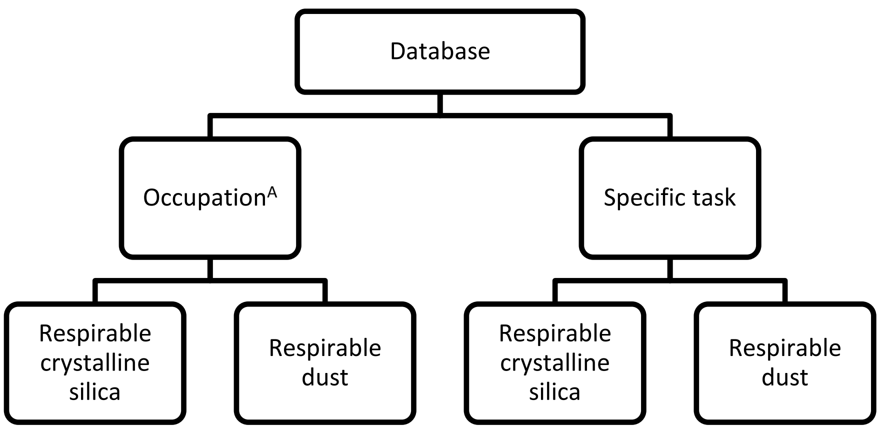


Figure 1 – Process of creating the four subsets of the database

[A] Contains the categories "8-hr TWA" and "Regulatory compliance" of the "Measurement objective" parameter of the database

Each of the four sub-databases was then limited to the lines of data meeting the following criteria:

- The quality score of the information provided on the determinants and the metrology had to be acceptable or excellent[4].
- Sampling had to have been done in the breathing zone.
- The sampling duration had to be available.
- For the crystalline silica measurements, the analysis had to have been performed according to a referenced method (e.g., IRSST method 206-2[5]) or a method derived from a referenced method. In the case of respirable dust, the data were limited to the samples analyzed by gravimetric determination.
- The working conditions evaluated had to be representative of the real conditions in the construction industry. Studies involving an experimental design and the control of sources of environmental variability were therefore excluded.
- The geometric mean and the geometric standard deviation, or the statistical parameters allowing a geometric mean and a geometric standard deviation to be calculated, had to be available for the lines of data presenting a result summarizing a number of exposure measurements equal to or greater than two.
- The description of the occupation (for the analysis by occupation) or the task (for the analysis by task) had to be available. For the tasks, the exposure data associated with more than one task during the sampling period were excluded.

For the analysis of the exposure levels by occupation, the data corresponding to two categories of the "Measurement objective" parameter in the database, namely "Regulatory compliance" and "8-hr time-weighted average (TWA)," were selected. The measurements associated with regulatory compliance in the database are mainly results collected during inspections performed by the U.S. Occupational Safety and Health Administration (OSHA). The other measurements whose objective was to document the exposure levels to compare them to an 8-hr OEL were assigned by default to the "8-hr TWA" category during the database compilation process. For purposes of clarity, the term "8-hr TWA" was replaced by "Surveillance" in our analyses.

[4] The quality scores of the descriptive parameters on the determinants and the metrology for each result in the database were assigned by its authors during the data entry step and are presented in Appendix 3 of IRSST report R-771 [24].

[5] http://www.irsst.qc.ca/-RSST14808-60-7.html

2.1.2 Processing of partial-period exposure data

In the case of measurements intended for comparing the exposure levels to an OEL, some data in the database were identified as two or more consecutive periods sampled during the same work shift and on the same worker. The results for these lines of data were merged by calculating a weighted average concentration over the total sampling period (Equation 1).

$$WAC = \frac{C_1 t_1 + C_2 t_2 + \ldots + C_n t_n}{t_1 + t_2 + \ldots + t_n} \quad (1)$$

Where WAC: weighted average concentration; C_n: average concentration for the partial period n; t_n: sampling duration for the partial period n.

For each result calculated as a weighted average from partial periods, a single line of data was retained in the sub-database, representing the total duration of the evaluation. For example, if three lines of data were identified as being partial periods sampled during the same work shift on a worker, a single line was retained for the analysis; the concentration and the duration associated with the partial period were then replaced by the weighted average concentration and the total sampling time for the three samples.

2.1.3 Processing of exposure data presented as summary parameters

The database identifies exposure values associated with a single sample ("single measurements") and values summarizing two exposures or more in the form of summary parameters such as the geometric mean and geometric standard deviation (GM and GSD). By using an original method developed by Lavoué et al. [27], the difficulties associated with the analysis of heterogeneous data can be avoided by recreating the original sample (by means of Monte Carlo simulation) from the results presented in the form of summary parameters. Once the simulation has been carried out, the data can be analyzed by using the standard methods for analyzing exposure determinants, such as linear models and their derivatives [28]. The approach of Lavoué et al. has recently been mentioned as being a possible alternative to the traditional analyses of literature synthesis combining individual measurements and summary parameters [29].

The first step in this method consists of standardizing the summary parameters by estimating the corresponding GM and GSD. For the lines of data whose results were presented in another form, the GM and GSD were estimated from the other reported statistical parameters, namely the arithmetic mean and the arithmetic standard deviation, the median and/or the range. The equations allowing this transformation are based on the properties of the lognormal distribution, which has been shown to adequately model workplace exposure [30], and are presented in Lavoué et al. [27]. If the lognormal distribution corresponding to the reported summary parameters is known, a number of measurements can be generated by simulation that are equal to the size of the original sample and consistent with its original distribution (Equation 2).

$$x = \exp[\ln(\text{GM}) + z \text{ x } \ln(\text{GSD})] \quad (2)$$

Where x: individual exposure value; z: random value taken from a standard normal distribution N(0.1).[6]

The individual exposure values thus created can then be added to the single measurements and analyzed together using methods adapted to the sets of data consisting of single exposure measurements.

2.1.4 Processing of nominal variables

For certain variables presented in Table 1, the categories containing a small number of measurements were aggregated. Processing was done by combining the categories considered similar *a priori* (judgements made by authors JFS and CB) or by combining them in an "Other" category. For example, the "indoor" environment category contains the enclosed, confined (e.g., stairwell, tunnel) and closed space categories, while the measurements originating from the industrial, institutional and commercial sectors were combined in the "Industrial/Institutional and Commercial" category. The "Local exhaust ventilation near the tool" and "Local exhaust built into the tool" source control methods were also grouped to create the "Local exhaust" category for the analysis of task-related exposure levels.

The occupation and task categories associated with fewer than 10 measurements were respectively grouped in the "Other" and "Other tasks" category. For the latter, new categories were then created from the task description in the documentary source, namely "Foundation work," "Excavation work," "Other roadwork," and "Other masonry-related tasks." Also, the distinction between the five sub-categories for the occupation of underground worker in the database (surveyor, driller, pipeline labourer and specialized labourer, others) was eliminated due to an insufficient number of measurements.

The data selection process presented in section 2.1.1 indicates the exclusion of lines of data where the description of the occupation and/or task was missing. For the other nominal variables, the lines of data where one or more of these parameters were not documented were retained in the analyses and identified by the "Not specified" category.

2.1.5 Descriptive analysis of the exposure determinants

Each of the four sub-databases was the subject of a descriptive analysis in order to orient the modeling strategy and the selection of the variables included in the process. Geometric means and geometric standard deviations were calculated on all of the measurements and for each category of nominal variable. Also, the preliminary analyses identified the presence of results whose reported concentration was below the limit of detection of the analytical method in the four sub-databases, particularly for the respirable crystalline silica samples. To take into account the undetected values in the calculation of the GMs and GSDs, we used the "Robust regression on order statistics (Robust ROS)" [31], known to perform better than the substitution methods

[6] For example, using the NORM.INV(RAND(),0,1) function in Excel software.

traditionally used in occupational hygiene [32], and recently applied to the analysis of occupational exposure data [23,33].

Considering the probabilistic nature of the simulation, the GMs and GSDs for all of the measurements and for each stratum of the different analyzed variables were calculated by repeating the simulation procedure 100 times. For each repetition, individual exposure values were simulated for the concentrations reported in the form of summary parameters and then combined with the single measurements. The overall GMs and GSDs and the GMs and GSDs for each stratum of the determinants were then calculated. The median values of the GMs and GSDs through the 100 repetitions were used as a final estimate. We also estimated the variability caused by the simulation by calculating relative standard deviations (RSDs)[7].

2.2 Statistical modeling of the crystalline silica exposure levels

2.2.1 Modeling strategy

The simultaneous influence of the different determinants on the exposure levels was estimated by performing multivariate statistical modeling for each sub-database. Statistical modeling consists of explaining the relationship between a response variable—in our case the respirable crystalline silica concentrations—and one or more predictive variables (e.g, workstation, task performed, work environment, etc.). The presence of a variable in the model implies that it has an impact on the response. On the contrary, the absence of a variable from the final model implies that it is not associated with the response; equivalently, it implies that the value of the coefficients associated with the variable is zero.

The statistical modeling procedure used in this study is based on a technique from ecology [34,35] and recently used to analyze occupational exposure data [36,37]. It is based on the *a priori* definition of a group of plausible models, constructed from unique combinations of the variables of interest. Thus, contrary to traditional approaches, the inference is based on multiple models. The final results are obtained by combining the results of all the models by using weights related to the goodness of fit of each model to the data. In the context of our analyses, the goodness of fit of each model was measured using a corrected Akaike information criterion (AICc) [38]. The weighting factor of each model is a value ranging from 0% ("poor" model) to 100% ("good" model), and the sum of the weights across all the models in the model set is equal to 100%. Thus, contrary to more traditional approaches, such as stepwise regression, which lead to the selection of a single final model, this approach allows the integration of information from several plausible models, and the uncertainty associated with the selection of a single model to be taken into account [39,40].

The "multimodel" regression coefficients are obtained by calculating an average of the coefficients of each of the models, with each individual value being adjusted by the weight of the corresponding model. For a variable missing from a model, the coefficients take the value of 0; a variable present only in models with a low weighting factor (namely with a poor goodness of fit) will have an attenuated effect, a phenomenon called "shrinkage."

[7] Relationship between the arithmetic standard deviation and the arithmetic mean or the median of the estimates across all repetitions, expressed as a percentage.

Tobit regression models [41,42] were used to take into account the presence of non-detected values in the analysis of the four sub-databases. Since the simulation of individual exposure values derived from the results reported in the form of summary parameters involves a random component, it must be repeated several times. Thus, statistical modeling of the exposure levels for each sub-database was applied to each of 20 repetitions of the simulation procedure detailed in section 2.1.3. For each repetition, the multimodel procedure was applied to the shared single and simulated measurements to calculate the multimodel coefficients. The final value of each multimodel coefficient was obtained by taking the arithmetic mean of their values across the 20 repetitions of the simulation procedure. The variability in the values of the coefficients caused by the simulation was estimated by computing their relative standard deviations across the 20 simulations.

2.2.2 Selection of the variables included in the modeling process and creation of sets of plausible models

2.2.2.1 Selection of the variables included in the modeling process

The data-input template of the database consists of 77 fields per line, which comprises the contextual and analytical information reported in the different publications, as well as the quantitative exposure level. The potential variables were first limited to the coded parameters, eliminating, for example, the fields containing non-standardized information such as general comments and free-text descriptions of the analytical and/or the control method used. Then, only variables whose description was available for a sufficient proportion of measurements were retained. During this step, the parameters related to respiratory protection, to the presence of a source of secondary exposure, and to the silica content of the bulk material were excluded.

The parameters related to the sampling and analytical methods were not included in the modeling process. For the respirable crystalline silica samples, the documented analytical methods were based on X-ray diffractometry or infrared spectrophotometry, which produce similar results [43,44], although the latter has a slightly lower specificity [45]. As for the sampling instrument, several models of cyclones (e.g., Dorr-Oliver, Higgins-Dewell) and cascade impactors were represented in the different sub-databases. However, the potential influence of the sampler used on the measured concentrations could not be evaluated because some determinants were associated with only one type of cyclone. Also, while the design and the recommended flow rate can vary with the type of apparatus, the differences are relatively minor between the fractions sampled by the instruments present in the four sub-databases and the respirable dusts as defined by the ACGIH and international standardization organizations [46-48]. Since the data were limited to samples analyzed and collected according to referenced methods (or methods related to these methods), the differences potentially due to these parameters on the measured concentrations were considered to be negligible in the context of our analyses. The variables retained in the modeling process for each analysis are presented in Table 1.

Table 1 – Variables included in the modeling process

Variable	Type	Analysis	
		Occupation	Task
Duration (ln(min))[A]	C[B]	X	X
Sampling year	C[B]	X	X
Occupation	N[C]	X[D]	
Task performed	N		X[D]
Activity sector	N	X	X
Project type	N	X	X
Sampling strategy	N	X	
Environment	N	X	X
Control (use)[E]	N	X	
Source control (type)	N		X[D]
Ventilation (dilution)	N		X

[A] Duration of sampling in minutes following logarithmic transformation
[B] Continuous numerical variable
[C] Nominal variable
[D] Variable present in all the candidate models in the set of models
[E] Use or not of a control method, without consideration of the specific type

2.2.2.2 Creation of sets of plausible models

The multimodel approach involves the definition of a set or list of plausible models containing combinations of single explanatory variables. For example, if there are three variables of interest (A, B, C), a list of eight possible models can be defined: one intercept-only model (corresponding to the absence of any influence by the three variables), three models with a single variable (A, B, or C), three models with two variables (AB, AC, BC), and one model containing all the variables (ABC). Prior knowledge can be used beforehand to include a certain number of models in the list or to exclude them from it.

The development of the sets of models for the analysis of exposure by occupation was initiated by the decision to include the standardized occupation variable in all of the models tested. The set of models was then constructed by using all possible combinations (presence/absence of the seven other variables presented in Table 1). This approach resulted in a preliminary list of 128 models. Three interaction terms were then added to the modeling process. With the interactions, the possible modification of the relationship between the response and a variable can be modeled as depending on the value of another variable. For example, the measurements in this sub-database were associated with two categories of sampling strategies, namely the evaluation of regulatory compliance, and exposure surveillance. To evaluate whether the exposure time trends were different between the two categories of strategies, an interaction between the sampling year and sampling strategy variables was integrated into the modeling process. Without this interaction, the time trend could be interpreted as being identical for both strategies. An interaction between the strategy variable and the sampling duration was also integrated into the modeling process, since we observed generally shorter sampling durations for the data collected during inspections. Finally, an interaction between the environment and the use of a control method was tested in order to evaluate the influence of the use of a control method during work performed either outdoors or indoors. It should be noted that, for an interaction term to be added between two variables in a model, the variables must necessarily be present in the model. As an example, an interaction between variables A and B in a multimodel procedure is added as follows: if the list contains 100 models, where 25 contain the two variables A and B, 25 identical models to which the interaction term has been included are added to the list. Following the addition of the three interaction terms mentioned above to the modeling process, the set of plausible models for this analysis contained 260 models.

For the analysis of exposure levels in relation to tasks, the list of models was initiated with the decision to include the *task performed* variable and *type of control method* variable in all the models. As in the analysis of exposure by occupation, the set of models was constructed from all the presence/absence combinations of the six other variables listed in Table 1, for an initial list of 64 models. In addition, the information on general ventilation associated with the measurements in the data sources was entered in the database in the form of presence/absence, with presence being both mechanical ventilation indoors and strong wind outdoors. To take into account potentially different effects between the presence of air currents outdoors and mechanical ventilation indoors, an interaction between the ventilation and environment variables was integrated into the modeling process for a final set consisting of 80 models.

The crystalline silica concentrations as well as the sampling duration were logarithmically transformed prior to model fitting, while the sampling year was normalized by subtracting the minimum value for the year in each sub-database. For the nominal variables, the category with the largest number of measurements (excluding the "not specified" category, when present) was selected as reference level.

2.2.3 Estimation of exposure levels by occupation and by task

The exposure levels by occupation and by task were estimated from predefined prediction scenarios. For each nominal variable other than the occupation or the task, the predictions were established by giving an equal influence to all the categories, except for the "not specified" category (when present). The aim of this approach was to standardize the predicted levels based on a balanced distribution of the various circumstances associated with crystalline silica exposure. A few adjustments had to be made, however, for certain occupations and for certain tasks associated with a limited number of working conditions in their respective sub-databases (Table 2). For example, only the effect of the outdoor environment was used for the predictions of exposure levels for the "Diamond cutting of concrete or asphalt" task, since all the measurements were collected under these conditions. Furthermore, since certain tasks, for example those involving manual work, were not compatible with all the control methods evaluated, the predictions for this analysis were made by assuming that there was no control method.

Table 2 – Modifications to prediction scenarios for the environment and activity sector variables

Exposure by occupation	Modifications to prediction scenario
Roofer	Environment = Outdoors Sector = Residential
Driller	Environment = Outdoors
Underground worker	Environment = Indoors Residential sector excluded
Exposure by task performed	**Modifications to prediction scenario**
Diamond cutting of concrete or asphalt	Environment = Outdoors Sector = Civil engineering and roadwork
Foundation work	Environment = Outdoors Sector = Civil engineering and roadwork
Excavation work	Environment = Outdoors Sector = Civil engineering and roadwork
Tunnel boring	Environment = Indoors Sector = Civil engineering and roadwork

For the year variable, the median value of the year of evaluation for all of the data, by sub-database, was integrated into the prediction scenario for each analysis. For duration of sampling, the exposure levels by occupation were predicted for an eight-hour sampling duration in order to compare the results to OELs. For exposure in relation to the nature of the task, we used the median sampling duration by category to take into account the duration of execution of the different operations.

The aim of the previously described scenarios was to estimate the overall exposure levels by considering a balanced distribution of the circumstances represented in the sub-databases. However, more specific predictions can be obtained from the characteristics of a given workplace for the tasks or workstations. In this regard, an example of the calculation of the geometric mean from multimodel coefficients is presented in Appendix 6.

The prediction of exposure levels was applied by using 20 repetitions of the Monte Carlo simulation procedure. For each repetition, the exposure levels by occupation or by task were estimated for each of the models and then combined using each model's weighting factor. The average value for the 20 repetitions was used as a final estimation, and the variability of the predictions across the 20 repetitions was evaluated by calculating the RSD.

2.3 Statistical modeling of respirable dust exposure levels

The modeling of respirable dust exposure levels followed the same procedures used for crystalline silica. To model the exposure by occupation, the project type variable and the interaction between the environment and the use of a control method had to be excluded from the group of models due to the unequal distribution of the data between the categories, resulting in a group of 104 models. For the analysis of task-related data, the group of models was identical to the corresponding analysis of the crystalline silica samples (80 models). To facilitate the comparison to the respirable crystalline silica results, the same reference categories for the nominal variables were used for the two analyses.

The standardized exposure levels were predicted for the respirable dust in relation to occupation and the nature of the task performed by using the same scenarios as for the crystalline silica analyses. The agreement between the predicted GMs for respirable crystalline silica and respirable dust (for the categories present in the two analyses only) was evaluated by calculating the Spearman correlation coefficient, a non-parametric metric. A value of 1 means that the order of the predicted GMs by category for crystalline silica is exactly the same as for respirable dust; however, a value of -1 indicates that the order of the predicted GMs between the two contaminants is completely reversed. A value of 0 for the coefficient indicates that there is no relationship between the predicted GMs for crystalline silica and those for respirable dust for the occupations and/or tasks.

2.4 Analysis of the crystalline silica content of the respirable dust samples

Analysis of the respirable crystalline silica percentages required three data selection steps in addition to the restriction criteria listed in section 2.1.1:

- Only the lines of data associated with single measurements were retained.
- Only the samples associated with a value for respirable dust as well as respirable crystalline silica were retained.
- Only the lines of data where the respirable crystalline silica concentration was greater than the limit of detection were retained.

Following these restriction steps, the data associated with the occupations and tasks were combined. The respirable crystalline silica percentage was calculated by dividing the reported concentration for each crystalline silica result by the corresponding concentration of respirable dust.

The 10th, 25th, 75th and 90th centiles were used to represent the distribution of the percentages for all of the data by category of the following predictors: occupation, task, tool, material and source control method. The calculations were performed using R software [49]

3. RESULTS

3.1 Exposure data retained

Approximately 87% of the database data originated from samples collected for comparison with an OEL or during the performance of a task. The 795 lines of data excluded in the first restriction step were those with an unknown sampling strategy (N=763), and a few lines (N=32) where the strategy was clearly identified as applying the worst case scenario principle. Restriction based on the sampled contaminant eliminated an additional 418 lines of data. The numbers of lines of data retained in relation to the restriction criteria are shown in Figure 2.

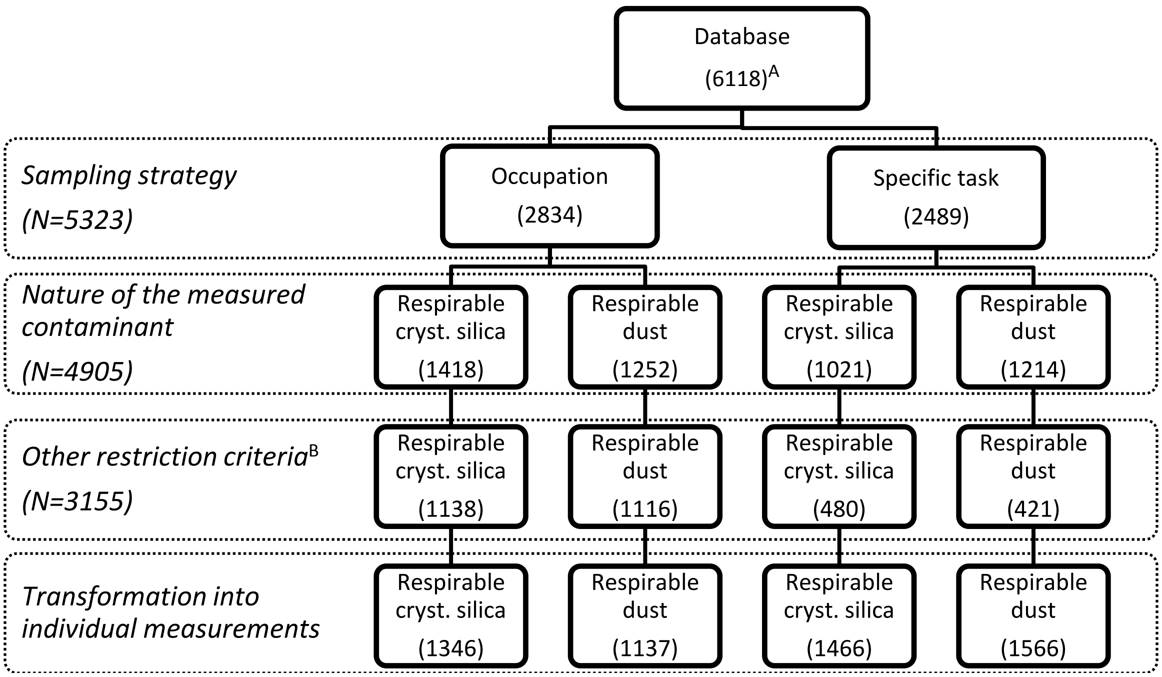


Figure 2 – Number of lines of data retained based on the restriction process

[A] Number of lines of data retained in the database or sub-databases after the restriction steps described in section 2.1.1

[B] For the analyses by occupation, this step includes the combination of lines during calculation of the weighted average concentrations, as described in section 2.1.2

For the sub-database containing the crystalline silica measurements collected for purposes of comparison to an OEL, the number of lines of data retained was 1138, including 39 weighted average concentrations calculated from 85 lines of data, and excluding 12 samples associated with the occupation of boilermaker where all of the concentrations were below the limit of detection. The latter were excluded from our analyses since no method allows valid descriptive statistics to be obtained with a percentage of undetected values above 80% [31,50,51]. The 1138 lines of data represented 1346 individual measurements. For the respirable dust samples, 1116 lines of data were retained, where 941 were associated with a respirable crystalline silica result.

For the data collected for the purpose of documenting the levels during a task, 421 lines of respirable dust and 480 lines of respirable crystalline silica were retained, with 324 being associated with the two contaminants. Compared to the two other sub-databases, the proportion of lines of information eliminated by the restriction process was much greater. This observation is explained by a higher share of samples collected in the ambient environment or at the source and/or analyzed by means of direct-reading instruments. Many results from experimental studies evaluating the efficiency of control methods under controlled conditions were also eliminated. Following the transformation of the concentrations reported as summary parameters described in section 2.1.3, the total number of individual values was 1466 for crystalline silica and 1566 for respirable dust.

The number of sources of data and the percentage of individual values by type of document for each sub-database are presented in Table 3. The majority of the documents used were research reports from public organizations, in particular those of the U.S. National Institute for Occupational Safety and Health (NIOSH). In terms of number of measurements, however, the main sources were the database of Flanagan et al. [8] for the analyses of exposure by occupation, and the articles from scientific journals for the analysis of task-related levels.

Table 3 – Distribution of sources of data by type of document

	Occupation		Specific task	
Type of document	**Cryst. silica**	**Dusts**	**Cryst. silica**	**Dusts**
Journal article	3[A] (17%)[B]	1 (3%)	20 (77%)	15 (79%)
Report from public org.	28 (36%)	26 (33%)	25 (17%)	24 (14%)
Database	1 (47%)	1 (64%)	1 (7%)	1 (7%)
Total	32	28	46	40

[A] Number of sources of data
[B] Percentage of individual exposure values. Since they are rounded percentages, the total cannot equal 100%.

3.2 Descriptive analysis of the exposure data

Table 4 presents the number of individual exposure values, the proportion of undetected and simulated values, the time period covered, and the overall GMs and GSDs for each sub-database. The GMs and GSDs reported in Table 4 include the minimum value, the median value and the maximum value of these estimates for the 100 repetitions of the simulation procedure. The descriptive results (e.g., sample sizes, GM and GSD) by category for each nominal variable documented in Table 1 are presented in Table 5 for occupation-related data, and in Table 6 for task-related data.

Table 4 – Sample size, proportion of undetected values and simulated values, period covered, total geometric mean and total geometric standard deviation by analysis and by contaminant

	Occupation		Specific task	
Contaminant	**Cryst. silica**	**Dusts**	**Cryst. silica**	**Dusts**
N [A]	1346	1137	1466	1566
%ND [B]	24%	<1%	6%	<1%
%simulated [C]	17%	2%	71%	77%
Period covered	1991-2006	1991-2006	1988-2007	1988-2005
GM (mg/m^3) [D] (min-max)	0.08 (0.08-0.09)	1.1 (1.1-1.1)	0.05 (0.05-0.05)	0.80 (0.76-0.86)
GSD [E] (min-max)	6.0 (6.0-6.1)	5.5 (5.5-5.5)	8.7 (8.3-9.2)	6.6 (6.2-7.0)

[A] Total of the individual exposure values
[B] Percentage of values reported as below the limit of detection
[C] Percentage of individual exposure values simulated from the summary parameters
[D] Geometric mean calculated for all of the individual values (median and range of 100 repetitions)
[E] Geometric standard deviation calculated for all of the individual values (median and range of 100 repetitions)

The period covered by all of the data contained in the four sub-databases totaled close to 20 years. The number of samples whose respirable crystalline silica concentration was undetected was 318 (24%) for the analysis by occupation and 94 (6%) for the task-related data.

For the occupation analysis, a significant difference between the two categories of sampling strategies (regulatory compliance and surveillance) was noted in the sampling duration. For the regulatory compliance data, the median of 170 minutes for both contaminants was less than half the median duration for the surveillance data, with 459 minutes (crystalline silica) and 410 minutes (dust). For the task-related data, the median value of the sampling duration was 334 minutes for crystalline silica, and 315 for dusts.

Table 5 – Descriptive results for the data for the analysis by occupation

	Crystalline silica							Dusts						
	n[A]	nE[B]	ND[C] (%)	SS[D] (%)	GM[E] (mg/m^3)	RSD[F] (%)	GSD[G]	n	nE	ND (%)	SS (%)	GM (mg/m^3)	RSD (%)	GSD
Total	1346	33	24	17	0.08	1	6.0	1137	28	<1	2	1.1	<1	5.5
Occupation														
Other	57	4	60	0	0.05	0	4.3	89	6	0	0	0.89	0	5.1
Bricklayer-mason	234	8	21	22	0.13	1	6.9	204	6	0	0	1.9	0	6.5
Boilermaker								12	1	0	100	0.28	10	1.4
Cement finisher	146	9	16	24	0.15	5	7.0	114	7	1	0	2.8	0	5.6
Foreman	13	4	8	62	0.04	6	1.9							
Roofer	53	5	0	0	0.15	0	2.4	59	5	0	0	1.1	0	2.2
Driller	12	4	8	0	0.21	0	3.4	10	3	0	0	1.5	0	7.7
Labourer (unskilled)	226	9	28	21	0.06	1	6.9	190	7	0	0	0.90	0	5.5
Pipeline labourer	58	4	29	0	0.10	0	4.7	53	3	0	0	2.7	0	4.5
Specialized labourer	357	18	23	17	0.07	1	4.5	256	14	0	0	1.1	0	4.9
Heavy equipment operator	153	10	29	8	0.05	2	3.6	150	9	0	9	0.37	2	3.2
Underground worker	37	3	8	32	0.26	7	5.9							
Activity sector														
Civil engineering and roadwork	368	12	23	11	0.05	1	4.5	278	10	0	5	0.47	1	4.6
Industrial, institutional and commercial	175	16	23	0	0.10	0	6.4	183	15	0	7	1.5	1	4.6
Residential	82	9	0	4	0.13	1	2.7	66	7	0	0	1.2	0	2.4
Not specified	721	5	27	25	0.10	1	6.5	610	4	0	0	1.5	0	5.9
Project type														
New construction	105	14	27	3	0.06	1	6.2	74	11	0	0	0.69	0	6.0
Demolition	115	5	1	24	0.09	3	3.3	20	4	0	0	1.6	0	3.0
Renovation	251	11	28	6	0.05	1	5.5	253	10	0	10	0.44	1	4.3
Not specified	875	9	25	21	0.11	1	6.0	790	7	0	0	1.6	0	5.3

	Crystalline silica							Dusts						
	n[A]	nE[B]	ND[C] (%)	SS[D] (%)	GM[E] (mg/m³)	RSD[F] (%)	GSD[G]	n	nE	ND (%)	SS (%)	GM (mg/m³)	RSD (%)	GSD
Sampling strategy														
Regulatory compliance	644	2	33	0	0.11	0	8.2	412	27	0	6	0.58	1	4.5
Surveillance	702	30	15	33	0.07	1	3.8	725	1	0	0	1.6	0	5.5
Environment														
Outdoors	451	25	22	7	0.06	1	4.9	365	21	0	4	0.53	1	4.4
Indoors	77	8	3	16	0.15	3	3.5	43	8	0	28	1.4	3	4.0
Not specified	818	4	26	22	0.10	1	6.4	729	3	0	0	1.6	0	5.5
Control (use)														
No	267	20	16	12	0.08	1	4.5	205	16	1	3	0.67	1	4.3
Yes	242	18	22	5	0.06	1	4.4	182	17	0	4	0.72	1	4.7
Not specified	837	5	27	22	0.10	1	6.8	750	4	0	2	1.4	0	5.7

[A] Total of the individual exposure values
[B] Number of sources from which the exposure values were taken
[C] Percentage of undetected values
[D] Percentages of simulated individual exposure values
[E] Geometric mean (median of the 100 repetitions)
[F] Relative standard deviation of the geometric mean across the 100 repetitions
[G] Geometric standard deviation (median of the 100 repetitions)

Table 6– Descriptive results for the data for the analysis by the task performed

	Crystalline silica							Dusts						
	n[A]	nE[B]	ND[C] (%)	SS[D] (%)	GM[E] (mg/m³)	RSD[F] (%)	GSD[G]	n	nE	ND (%)	SS (%)	GM (mg/m³)	RSD (%)	GSD
Total	1466	46	6	71	0.05	3	8.7	1566	40	<1	77	0.80	2	6.6
Task														
Spraying								13	1	0	100	0.04	31	3.1
Other masonry-related tasks	14	3	0	50	0.03	12	4.4	16	3	0	44	0.96	14	2.6
Other roadwork	47	4	6	51	0.02	9	3.8	34	3	0	71	0.18	13	3.7
Bush hammering (scabbling) concrete	12	2	50	0	0.44	0	3.1	12	2	33	0	2.9	0	5.2
Breaking - Other tools	21	4	10	0	0.13	0	7.4	17	2	0	0	1.6	0	5.9
Breaking - Jackhammer	56	2	7	0	0.46	0	2.7	63	2	0	0	3.5	0	2.7
Breaking - Multiple tools (including jackhammers/percussion drills)	88	3	6	93	0.94	13	4.7	83	2	0	99	11	13	3.5
Heavy equipment operation								35	2	0	94	0.07	28	6.7
Diamond cutting of concrete or asphalt	40	3	10	0	0.02	0	2.8	42	3	5	0	0.38	0	2.5
Abrasive blasting	23	5	4	61	0.81	22	6.3	23	5	0	61	7.1	29	8.8
Demolition	32	2	0	97	0.03	36	6.1	32	2	0	97	0.24	30	4.7
Manual moving of small rocks, soil, etc.	11	2	9	0	0.09	0	2.6							
Mechanized moving of rocks, soil, etc.	13	3	8	0	0.07	0	4.0	145	3	0	89	0.12	12	5.5
Tunnel boring	45	2	0	91	0.33	12	3.3	45	2	0	91	2.1	9	2.0
Installation of acoustic ceiling tiles	42	2	45	50	0.01	23	7.5	21	1	0	100	0.81	25	2.8
Mixing of cements and mortars	26	4	19	50	0.01	13	4.5	26	4	0	50	0.58	21	4.5
Brick/stone joint grinding	82	7	12	12	0.26	5	7.7	63	5	0	16	1.4	5	4.5
Surface grinding	213	5	0	99	0.07	6	8.6	213	5	0	99	1.2	8	7.7
Installation of concrete formwork	159	3	0	98	0.02	9	5.5	156	2	0	100	0.53	6	2.8
Cleaning	15	2	0	100	0.01	38	3.8	15	2	0	100	0.46	28	3.1

	Crystalline silica							Dusts						
	n[A]	nE[B]	ND[C] (%)	SS[D] (%)	GM[E] (mg/m^3)	RSD[F] (%)	GSD[G]	n	nE	ND (%)	SS (%)	GM (mg/m^3)	RSD (%)	GSD
Task (cont.)														
Drilling - concrete	45	8	31	36	0.06	12	10	27	5	0	52	1.8	18	2.9
Drilling - stone	122	3	0	98	0.03	11	3.9	122	3	0	98	0.98	8	2.5
Piercing - ground and stone	13	3	15	62	0.02	53	6.5	20	4	0	40	0.32	21	3.0
Sanding	31	2	42	0	0.05	0	7.2	36	2	0	0	2.4	0	2.5
Shotcreting	94	2	0	87	0.02	12	3.5	94	2	0	87	2.4	8	2.4
Sawing masonry	81	10	5	56	0.10	8	4.7	70	9	0	51	1.9	9	5.1
Foundation work	44	1	0	100	0.01	13	2.9	45	2	0	98	0.14	14	2.9
Electrical maintenance work	41	1	0	100	0.01	13	2.5	41	1	0	100	0.71	9	1.8
Excavation work	56	1	0	100	0.01	17	4.1	57	2	0	98	0.19	17	4.4
Source control method														
Water/tool	52	9	19	21	0.07	5	3.6	39	7	10	0	0.52	0	2.9
Water/surface	100	4	6	89	0.02	13	4.5	152	5	0	94	0.97	9	4.8
Water/surface + source isolation								121	1	0	100	0.06	15	5.2
Local exhaust ventilation	117	11	11	36	0.09	4	6.4	125	12	0	34	0.81	7	6.3
None	726	22	3	79	0.08	3	9.7	672	18	0	85	1.8	3	4.7
Other/Not specified	471	19	10	68	0.03	5	7.4	457	17	0	70	0.50	5	5.6
Activity sector														
Civil engineering and roadwork	838	16	3	89	0.02	4	5.4	984	14	0	93	0.42	4	5.1
Industrial, institutional and commercial	161	14	19	34	0.08	5	8.6	138	13	3	39	1.1	7	8.7
Residential	35	4	37	0	0.13	0	5.0	27	2	0	0	1.6	0	2.5
Other/Not specified	432	14	7	55	0.22	4	7.8	417	14	0	54	3.3	4	4.9
Project type														
New construction	823	13	1	97	0.02	4	5.8	996	13	0	98	0.43	4	5.6
Renovation	194	18	21	6	0.07	2	9.2	127	11	2	0	0.95	0	4.6
Other/Not specified	449	16	10	51	0.19	3	8.2	443	16	1	51	3.2	4	4.8

	Crystalline silica							Dusts						
	n[A]	nE[B]	ND[C] (%)	SS[D] (%)	GM[E] (mg/m^3)	RSD[F] (%)	GSD[G]	n	nE	ND (%)	SS (%)	GM (mg/m^3)	RSD (%)	GSD
Environment														
Outdoors	670	29	5	65	0.04	3	9.0	810	27	0.7	75	0.36	4	7.2
Indoors	583	17	9	73	0.04	4	6.5	524	11	0	79	1.6	3	2.8
Not specified	213	8	3	84	0.23	7	9.1	232	8	0	77	3.2	7	5.3
General ventilation														
No	474	29	10	49	0.20	3	7.1	532	25	1	64	1.1	4	12
Yes	535	6	1	91	0.03	5	6.0	588	7	0	92	0.85	4	3.5
Not specified	457	15	9	70	0.03	5	7.7	446	13	0	72	0.53	5	5.6

[A] Total of the individual exposure values
[B] Number of sources from which the exposure values were taken
[C] Percentage of undetected values
[D] Percentages of simulated individual exposure values
[E] Geometric mean (median of the 100 repetitions)
[F] Relative standard deviation of the geometric mean across the 100 repetitions
[G] Geometric standard deviation (median of the 100 repetitions)

3.3 Statistical modeling of crystalline silica and respirable dust exposure levels

3.3.1 Overall results

The coefficient of determination—or R^2—is a measure traditionally used to describe the goodness of fit of a model and the fraction of the variability in the exposure levels explained by it. For each sub-database, we calculated the value of the coefficient of determination of the "full" model, meaning the model in the set which contained all the variables and interactions. Since the Tobit model does not allow the computation of the R^2 statistic, we replaced the undetected values by dividing the value at the limit of detection by two [32] and fitted a linear regression model. Finally, this procedure, used solely to calculate R^2, was repeated 20 times to take into account the inherent variability of the individual exposure value simulation procedure. The minimum, average and maximum values of the coefficient of determination estimated with the substitution approach for the 20 repetitions by analysis are presented in Table 7. The average R^2 for the data analysis for comparing the crystalline silica exposure to a limit value was 22%, whereas it was 60% for the task-related data. The coefficients of determination obtained for respirable dust with the models were almost identical to those for crystalline silica in their respective analyses.

Table 7 – Coefficients of determination of the complete model by analysis and contaminant

	Occupation		Specific task	
	Cryst. silica	**Dusts**	**Cryst. silica**	**Dusts**
Average (%) [A]	22	21	60	60
Min-max (%) [B]	21–22	20–21	58–62	57–62

[A] Average value calculated for 20 repetitions
[B] Minimum and maximum values for the 20 repetitions

Table 8 presents the five best models based on their weighting factors in relation to the analysis and the nature of the contaminant sampled. For the analysis of the exposure levels by occupation, the sum of the weighting factors of the five best models for crystalline silica (out of 260) was 67% (average of the 20 repetitions). The difference between the weighting factors of these five models (from 7% to 25%) was relatively small, and suggests that no model stood out as being much more appropriate than the others. Furthermore, the average weight of the full model—used to calculate the coefficient of determination—was 2%, which ranked it 10th. The portrait was similar for respirable dusts with a total weighting factor of 62% for the five best models.

Table 8 – Five best Tobit models for the four sub-databases

Analysis	**Occupation**									
Contaminant	**Crystalline silica (260)[A]**					**Dusts (104)**				
Rank	1	2	3	4	5	1	2	3	4	5
Occupation	X[B]	X	X	X	X	X	X	X	X	X
Duration	X	X	X	X	X	X	X	X	X	X
Year	X	X	X	X	X	X	X	X		X
Sector	X	X	X	X	X	X	X	X	X	
Project type[C]	X	X	X	X	X					
Strategy	X	X	X	X	X	X	X	X		X
Environment			X			X	X	X	X	X
Control	X		X	X		X	X		X	X
Strategy/Duration interaction				X	X		X			
Strategy/Year interaction	X	X	X	X	X	X	X	X		X
Environment/Control interaction[C]										
Weighting factor[D] (%)	25	15	10	10	7	33	12	9	4	4

Analysis	**Specific task**									
Contaminant	**Crystalline silica (80)**					**Dusts (80)**				
Rank	1	2	3	4	5	1	2	3	4	5
Task	X	X	X	X	X	X	X	X	X	X
Source control	X	X	X	X	X	X	X	X	X	X
Duration	X	X	X				X		X	
Year	X	X		X	X			X	X	X
Sector	X	X	X	X	X	X	X	X	X	X
Project type	X		X		X	X	X	X	X	X
Environment	X	X	X	X	X	X	X	X	X	
General ventilation	X	X	X	X	X	X	X	X	X	X
Environment/Ventilation interaction	X	X	X	X	X	X	X	X	X	X
Weighting factor (%)	94	6	0	0	0	31	26	18	12	3

[A] Number of models in the set
[B] Indicates the presence of a variable in the model's structure
[C] Variable and interaction excluded from the analysis of the respirable dust data
[D] Average value across the 20 repetitions

For the analysis of crystalline silica exposure during a specific task, the full model had a weight of 94%, and the next best model, without the *project type* variable, 6%. The influence of the 78 other models on the results was therefore negligible since the estimation of the effects of the determinants and the predicted exposure levels was based mainly on a single model. The usefulness of the multimodel inference procedure was therefore relatively limited in this case.

This result was not observed for respirable dusts, with values of 31% and 26% for the two best models. The average weighting factor obtained for the model containing all the variables and the interaction term was 12%.

3.3.2 Effects of the exposure determinants

This section presents the effects of exposure determinants other than occupations and tasks, which will be discussed in the next section (3.3.3). The effects of the nominal variables (e.g., environment, control methods) are presented in percentages as relative exposure indices [52] and calculated from the multimodel coefficients. For each of these variables, the value of the reference category is taken as 100%. A category associated with an estimate above 100% indicates an increasing effect on the exposure levels; conversely, a value below 100% indicates a decreasing trend. For the sake of conciseness and due to their limited interpretation for the exposure levels, the effects associated with the "Not specified" categories are not presented in this section. For the continuous variables, namely the sampling duration and the year of the evaluation, their effects are expressed in a relative way as a percentage of increase or decrease by increment of the value of the variable. The regression coefficients obtained by multimodel inference are presented in Appendix 3 for the analysis of the "exposure by occupation" sub-database, and in Appendix 4 for the analysis of the "exposure during a task" sub-database.

Analysis of the "exposure by occupation" database

The effects of the studied determinants, accompanied by their 95% confidence intervals, are presented in Table 9. The decreases in the crystalline silica exposure levels associated with a 50% increase in the sampling duration (e.g., from 300 to 450 minutes) were 10% and 11% respectively for the surveillance data and the regulatory compliance evaluation data. A sharp difference in the time trends between the two sampling strategies was observed, with a 9% increase per year for the surveillance data, compared to a 17% reduction per year for the regulatory compliance evaluation data. For the latter, a much smaller reduction was observed for respirable dusts, with a reduction of 2% per year.

For the interaction between the environment and the use of control methods (without considering the specific type) on the crystalline silica exposure, the *outdoor environment/without control method* combination was selected as the reference level (100%). A relative index of 84% was observed for the *outdoors/with control method* combination, which can be interpreted as a 16% reduction in the exposure levels due to the use of a control method. Indoors, the *indoors/without control method* combination had a relative index of 119%, namely a 19% increase in exposure compared to the reference level (*outdoors/without control method*). A relative index of 98% was observed for the use of a control method indoors. The difference between the *indoors/with control method* combination (98%) and *indoors/without control method* combination (119%) indicates a 21% reduction in concentrations associated with the use of a control method. The interaction between the environment and the use of a control method could not be tested for respirable dust since some combinations of these two variables were not represented in the dataset. The separate analysis of these two variables for respirable dust showed that the concentrations in an indoor environment were close to four times higher than outdoors, while a 21% reduction in exposure was associated with the use of a control method.

Table 9 – Estimated effects of the exposure determinants (analysis by occupation)

	Contaminant	
	Cryst. silica	Dusts
Variable	**Effect (%)**	**Effect (%)**
Duration (+50%) [A]		
Surveillance	90 [80;101] [B]	92 [82;104]
Compliance	89 [82;97]	93 [86;100]
Year [C]		
Surveillance	109 [102;116]	106 [98;115]
Compliance	83 [78;89]	98 [92;104]
Sector		
Civil engineering and roadwork	Reference (100%)	Reference (100%)
Industrial, Institutional and Commercial	187 [110;318]	145 [96;220]
Residential	146 [70;304]	135 [41;447]
Project type		
Renovation	Reference (100%)	—
New construction	55 [30;103]	—
Demolition	107 [66;174]	—
Environment/Control method interaction		
Outdoors/Without control method	Reference (100%)	—
Outdoors/With control method	84 [58;121]	—
Indoors/Without control method	119 [64;224]	—
Indoors/With control method	98 [53;181]	—
Environment		
Outdoors	—	Reference (100%)
Indoors	—	382 [193;755]
Control method		
Without control method	—	Reference (100%)
With control method	—	79 [52;119]

[A] Effect of the 50% increase in sampling duration, stratified by strategy
[B] Estimated effect and 95% confidence interval (average values over 20 repetitions)
[C] Annual trend stratified by strategy; reference year: 1991

Analysis of the "exposure during a task" database

The effects of the studied exposure determinants and their 95% confidence intervals are presented in Table 10. A 50% increase in sampling duration was associated with a 19% reduction in respirable crystalline silica concentrations. The observed annual trend was an 11% reduction in exposure levels per year. These two effects were much smaller and non-significant for respirable dust: a 50% increase in sampling duration was related to a 2% reduction in the concentrations, and a 1% downward time trend per year.

Table 10 – Estimated effects of the exposure determinants (analysis by specific task)

	Contaminant	
	Cryst. silica	Dusts
Variable	**Effect (%)**	**Effect (%)**
Duration (+50%)[A]	81 [75;87] [B]	98 [93;104]
Year [C]	89 [85;94]	99 [96;103]
Project type		
New construction	Reference (100%)	
Renovation	91 [55;152]	260 [121;557]
Sector		
Civil engineering and roadwork	Reference (100%)	
Industrial, institutional and commercial	56 [33;95]	77 [47;126]
Residential	127 [57;283]	46 [18;122]
Source control method		
None	Reference (100%)	
Spraying/surface	43 [23;79]	165 [101;267]
Spraying/surface + source isolation	—	6 [3;13]
Spraying/tool	29 [15;54]	12 [7;24]
Local exhaust	31 [22;44]	19 [14;26]
Environment/General ventilation interaction		
Outdoors/With ventilation[D]	Reference (100%)	
Outdoors/Without ventilation	3763 [2302;6150]	884 [537;1455]
Indoors/With ventilation	1758 [1196;2585]	590 [426;817]
Indoors/Without ventilation	1789 [968;3308]	976 [545;1746]

[A] Effect of a 50% increase in sampling duration
[B] Estimated effect, 95% confidence interval (average values over 20 repetitions)
[C] Annual trend, reference year: 1988
[D] The "With ventilation" category for the outdoor environment indicates the presence of significant wind

The most effective control methods for reducing the standardized crystalline silica exposure levels, in relation to the "None" reference category, were spraying using a water-fed tool with a 71% reduction, and local exhaust with 69%. Spraying/wetting of the material was associated with a 57% reduction in exposure levels. The estimated rates of reduction were generally higher for respirable dusts, except for surface spraying, which was associated with a marginally significant increase in exposure (65%). Furthermore, material spraying combined with isolating the worker from the source produced the highest estimated effectiveness, but this category was present only for respirable dust. The data for this category originated from a single publication, and involved the use of a closed cabin (pressurized or not) on different types of road equipment (graders, scrapers and backhoes).

The largest effects were found with the interaction between the environment and general ventilation, particularly for crystalline silica. The activities performed outdoors in the presence of significant wind—namely the reference category—were associated with much lower crystalline silica and dust levels than for the other combinations present. For crystalline silica, levels 38 times lower were observed for the *outdoors/with wind* combination compared to the *outdoors/without wind* combination. For the indoor environment, the exposure levels were 18 times higher in relation to the reference combination (*outdoors/with wind*), with and without mechanical ventilation.

3.3.3 Predictions of exposure levels by occupation and by task

Exposure by occupation

The predictions of the geometric mean by occupation, standardized over 8 hours for exposure to respirable crystalline silica, accompanied by their 95% confidence intervals, are presented in Figure 3. The variability in the predicted GMs between the repetitions of the simulation procedure was relatively low, with RSDs below 3%, except for foremen (6%) and underground workers (5%).

The fractions of exposures exceeding the ACGIH *Threshold limit value* or TLV (0.025 mg/m^3) [53] and the TWAEV in the ROHS (0.1 mg/m^3) [26] for crystalline silica—representing, for example, the proportion of work shifts with an exposure above these thresholds—are presented in Table 11. The exceedance fractions were calculated from the predicted geometric means and by using the average value of the residual errors of the 260 models as the geometric standard deviation (5.17). Except for the "Other" category, the fractions of exposures exceeding the TLV were all above 50%, with the highest being found for underground workers and roofers with 91% and 92% (for example 9 out of 10 work shifts). The latter were roofers installing concrete tile roofing, a covering material that is used only exceptionally in Québec. As a result, the predicted exposure levels are therefore not representative of the exposure of all of the roofers working in the Québec construction industry. As for the estimated fractions exceeding the Québec TWAEV, they vary between 31% and 71%. The value of the Spearman correlation coefficient between the predicted GMs for silica and respirable dust was 0.45 (p value of 0.23), indicating a moderate agreement.

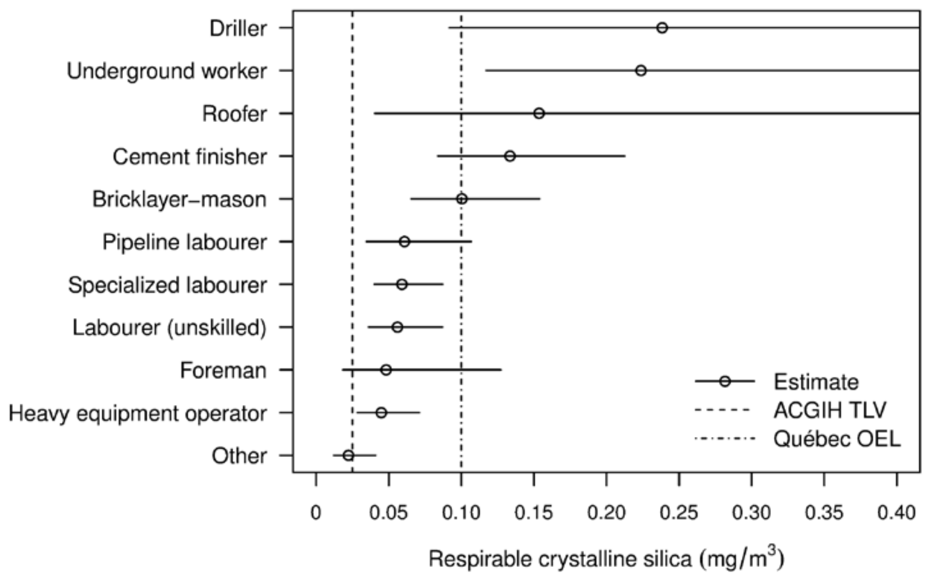


Figure 3 – Predicted geometric means for respirable crystalline silica exposure by occupation category (with 95% confidence intervals)

Table 11 – Predictions of standardized exposure levels and exceedance fractions by occupation category

Contaminant	Crystalline silica			Dusts
Occupation	GM (mg/m^3)[A]	F.TLV(%)[B]	F.TWAEV(%)[C]	GM (mg/m^3)[D]
Driller	0.24	92	70	1.8
Underground worker	0.22	91	69	–
Roofer	0.15	87	60	0.85
Cement finisher	0.13	85	57	2.9
Bricklayer-mason	0.10	80	50	2.0
Pipeline labourer	0.06	71	38	2.8
Specialized labourer	0.06	70	37	1.2
Labourer (unskilled)	0.06	69	36	1.2
Foreman	0.05	66	33	–
Heavy equipment operator	0.04	64	31	0.75
Other	0.02	47	18	0.86
Boilermaker	–	–	–	0.15

[A] Predicted geometric mean of respirable crystalline silica exposure (average of the 20 repetitions)
[B] Fractions of exposures exceeding the ACGIH threshold limit value
[C] Fractions of exposures exceeding the TWAEV in the ROHS
[D] Predicted geometric mean of respirable dust exposure (average of the 20 repetitions)

Exposure by task

For the crystalline silica samples, the predicted GMs were above 0.025 mg/m^3 (the ACGIH's TLV for an 8-hour exposure) for 11 of the 27 task categories. They are presented in Figure 4, accompanied by their 95% confidence intervals. All of the average exposure levels and median sampling durations by task category and by contaminant are presented in Table 12.

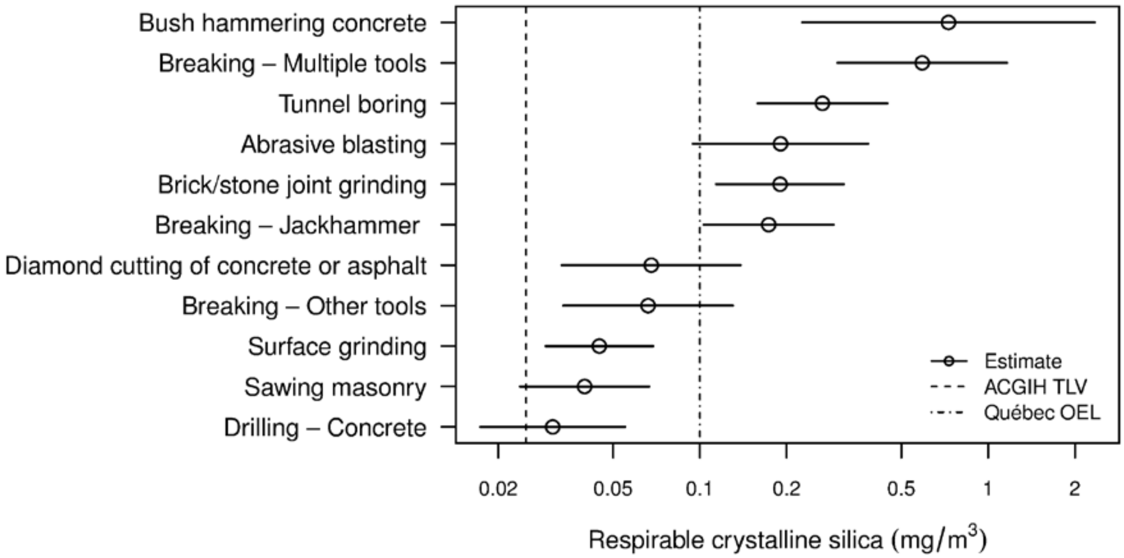


Figure 4 – Predicted geometric means for respirable crystalline silica exposure by task category (with 95% confidence intervals)

The "bush hammering concrete" category presented the highest predicted GM for crystalline silica with 0.73 mg/m^3, mainly due to the much shorter median sampling duration (5 minutes) relative to the other categories. The bush hammering task was followed by that of breaking with multiple tools (including jackhammers and/or percussion drills) with a geometric mean of 0.59 mg/m^3. The task involving breaking with multiple tools was also associated with the second highest predicted GM for dusts (5.8 mg/m^3), after that of abrasive blasting (6.8 mg/m^3). For abrasive blasting, documenting the exposure levels associated with this activity was outside the scope of the database creation project. Sampling results for this task were nevertheless entered in the database if they accompanied crystalline silica exposure results for other tasks in the publications.

The three categories involving a breaking task were among those generating the highest crystalline silica exposures, with GMs between 0.07 mg/m^3 (with other tools) and 0.59 mg/m^3 (with multiple tools including the use of jackhammers/percussion drills). Furthermore, sanding (1.9 mg/m^3) and acoustic ceiling tile installation (2.3 mg/m^3) tasks were among the five tasks with the highest predicted respirable dust GMs, while the corresponding predictions for respirable crystalline silica were equal to or below 0.02 mg/m^3.

Regarding the variations caused by simulation of the exposure levels, the predicted crystalline silica RSDs of the GMs by task varied between 5% (Breaking - Jackhammer) and 47% (Ground and stone drilling) with a median of 15%. For respirable dust, the median RSD was 18% with a minimum of 5% (Breaking – other tools) and a maximum of 37% (Heavy equipment operation).

The agreement between the ranks of predicted GMs for the two contaminants by task category was higher than for the occupation categories, with a Spearman correlation coefficient of 0.70 (p value below 0.01).

Table 12 – Predicted geometric means and median sampling durations by task category

	Crystalline silica		Dusts	
Task	**GM[A] (mg/m^3)**	**Duration[B] (min)**	**GM[C] (mg/m^3)**	**Duration (min)**
Bush hammering concrete	0.73	5	2.6	5
Breaking - Multiple tools (including jackhammers/percussion drills)	0.59	210	5.8	210
Tunnel boring	0.27	390	1.7	390
Abrasive blasting	0.19	315	6.8	315
Brick/stone joint grinding	0.19	256	1.8	212
Breaking - Jackhammer	0.17	81	1.8	59
Diamond cutting of concrete or asphalt	0.07	218	0.67	217
Breaking - Other tools	0.07	104	0.87	89
Surface grinding	0.04	309	1.7	309
Sawing masonry	0.04	210	1.3	210
Drilling - Concrete	0.03	390	1.0	390
Mechanized moving of rocks. soil. etc.	0.02	120	0.62	298
Demolition	0.02	334	0.58	334
Shotcreting	0.02	390	1.3	390
Drilling - stone	0.02	390	0.89	390
Sanding	0.02	185	1.9	142
Installation of concrete formwork	0.01	390	0.86	390
Manual moving of small rocks, soil, etc.	0.01	212	–	–
Piercing - ground and stone	0.01	283	0.26	163
Installation of acoustic ceiling tiles	0.01	320	2.3	315
Electrical maintenance work	0.01	390	0.65	390
Other roadwork	0.01	350	0.29	350
Other masonry-related tasks	<0.01	255	0.69	118
Cleaning	<0.01	390	0.37	390
Excavation work	<0.01	341	0.32	341
Mixing of cements and mortars	<0.01	336	0.79	336
Foundation work	<0.01	356	0.22	356
Spraying	–	–	0.34	228
Heavy equipment operation	–	–	0.32	286

[A] Predicted geometric mean for respirable crystalline silica exposure (average of the 20 repetitions)
[B] Median value of the sampling duration by category
[C] Predicted geometric mean for respirable dust exposure (average of the 20 repetitions)

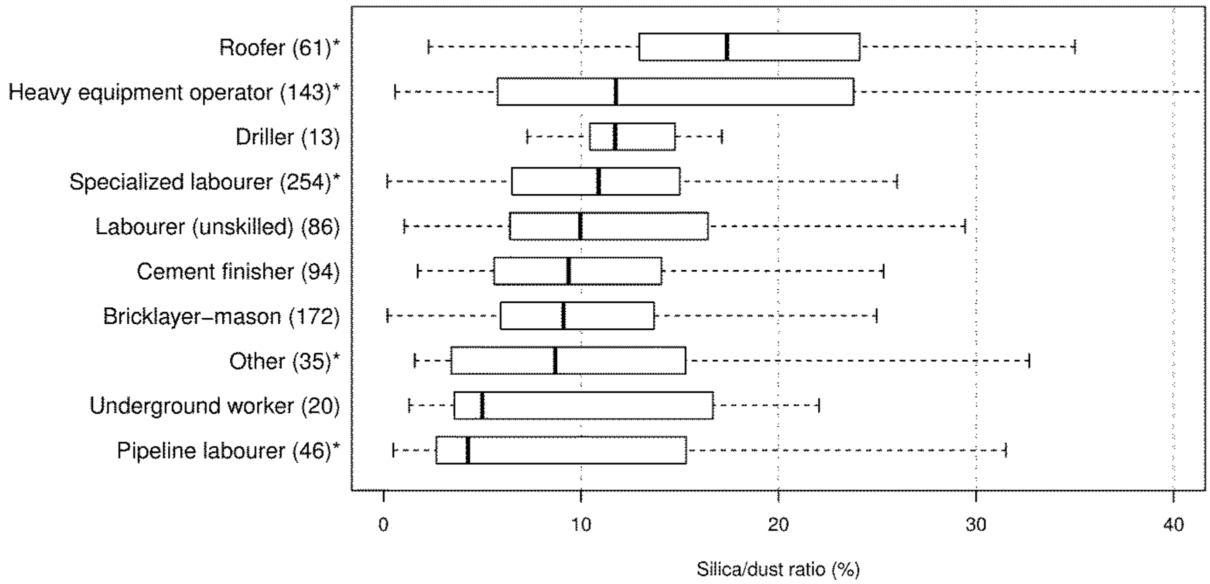
3.4 Descriptive analysis of the crystalline silica percentages

Combining the sub-databases according to the sampled contaminant resulted in the merging of 1618 and 1537 lines of data for crystalline silica and respirable dust, respectively. Of these, 1265 were single measurements associated with a crystalline silica result as well as a respirable dust result. Of this number, 339 results whose respirable crystalline silica concentration was below the limit of detection were excluded. In addition, two other results had a crystalline silica concentration equal to or greater than the dust concentration and were excluded, bringing the final number to 924 lines of data for which a dual crystalline silica/respirable dust concentration was available.

A strong association between the silica and respirable dust concentrations was observed, with a Pearson correlation coefficient of 0.92 (following a logarithmic transformation of the concentrations). The median crystalline silica percentage for the 924 lines of data was 11% (6%–16% interquartile interval, <1%–95% range), and a silica content equal to or greater than 24% for approximately 10% of the data. The distributions of the crystalline silica percentages by occupation, task, tool, material and source control method category are presented in the form of box and whisker plots (boxplots) in Figures 5 to 9. Briefly, boxplot graphs are used to represent the distribution of a group of values. They include the "box," which represents the interval of the distribution where the majority of data (50%) are concentrated, and the "whiskers," which provide a depiction of the spread of the distribution.

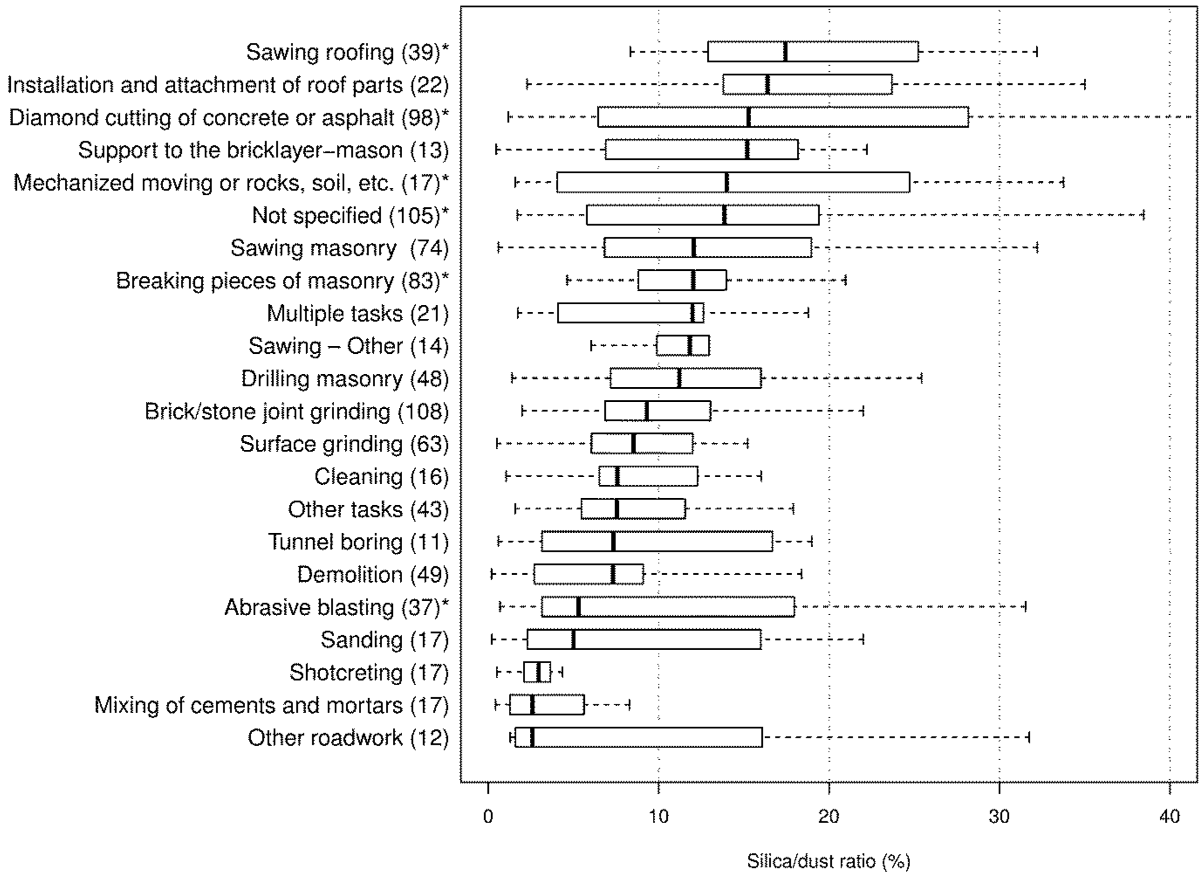
More precisely, the left and right boundaries of the box for each category in Figures 5 to 9 indicate the interval between the first quartile (Q1), equivalent to the 25th centile of the distribution, and the third quartile (Q3) or 75th centile. The median of the distribution is represented by the vertical line dividing the box in two. As for the extremities (whiskers), the lower limit represents the smallest value of the upper distribution at [Q1-1.5*(Q3-Q1)], while the upper limit indicates the highest value below [Q3+1.5*(Q3-Q1)]. To facilitate the reading of the diagrams, the extreme values (outliers, which would be outside the whiskers) have not been represented in Figures 5 to 9. Furthermore, the categories containing at least one sample whose crystalline silica content was equal to or greater than 50% are identified by an asterisk (*). The 10th, 25th, 50th, 75th and 90th centiles by occupation, task, tool, material and source control method category are presented in Appendix 3.

The median crystalline silica percentage for the occupation of roofer (17%) was much higher than those of the other occupations. All the measurements for this category were related to the tasks of sawing roofing and installing and attaching roofing, with medians of 17% and 16%, respectively. For materials, sand (19%) and asphalt (17%) had the highest median percentages. The measurements for the latter category were all related to the task of diamond cutting of concrete or asphalt and the use of a road-milling machine. The lowest median crystalline silica percentage was observed for the "acoustic tile" material category with 2% (range 1%–3%).



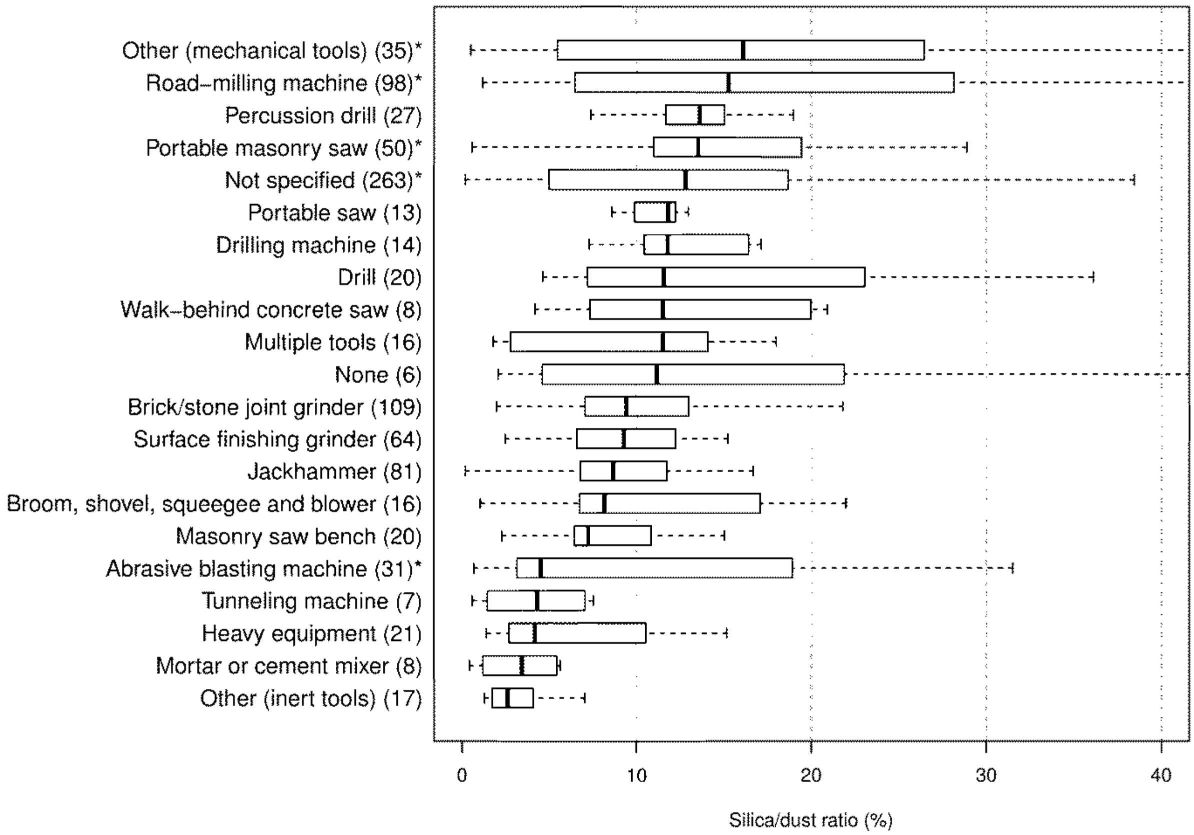
*The category contains at least one sample where the crystalline silica content of the respirable dust is equal to or greater than 50%.

Figure 5 – Respirable crystalline silica percentages by occupation category



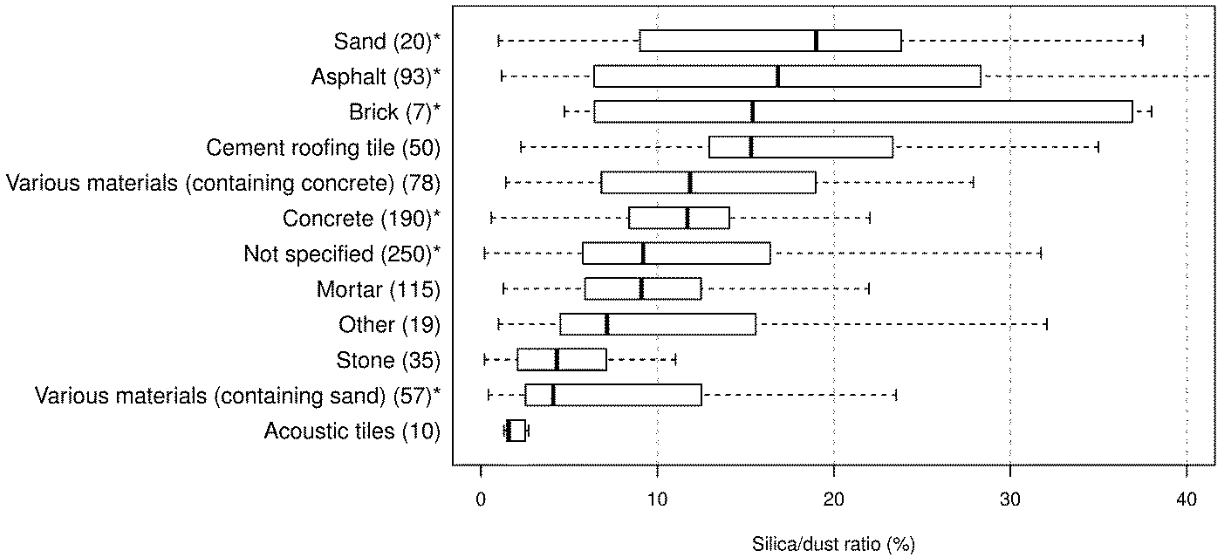
*The category contains at least one sample where the crystalline silica content of the respirable dust is equal to or greater than 50%.

Figure 6 – Respirable crystalline silica percentages by task category



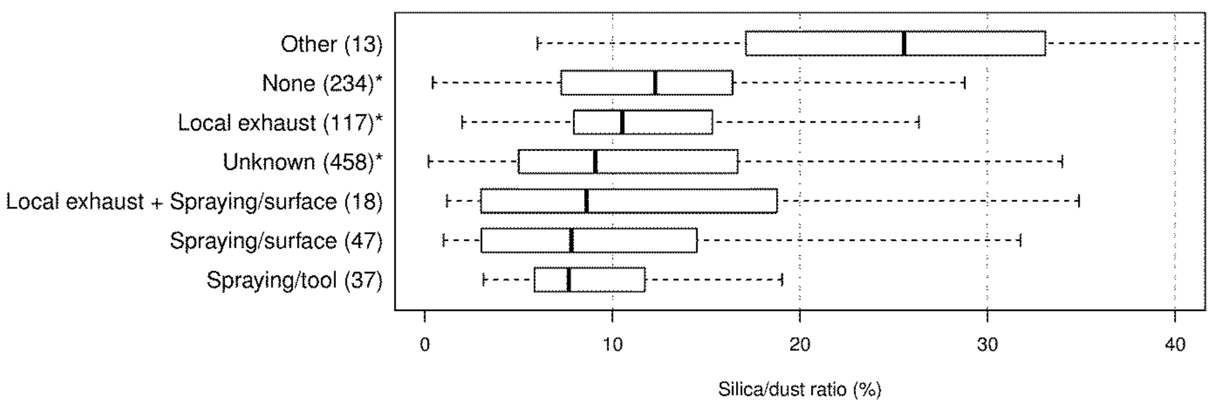
*The category contains at least one sample where the crystalline silica content of the respirable dust is equal to or greater than 50%.

Figure 7 – Respirable crystalline silica percentages by tool category



*The category contains at least one sample where the crystalline silica content of the respirable dust is equal to or greater than 50%.

Figure 8 – Respirable crystalline silica percentages by material category



*The category contains at least one sample where the crystalline silica content of the respirable dust is equal to or greater than 50%.

Figure 9 – Respirable crystalline silica percentages by source control method category

4. DISCUSSION

4.1 Exposure data retained

The data selection process led to the retention of 3155 of the 6118 lines in the database, or 52%, for our analyses. The proportion of lines of data retained was smaller for the analyses relating to the nature of the task performed, mainly due to the exclusion of measurements carried out during experimental studies that we considered as not being representative of the working conditions on construction sites. The aim of these studies was mainly to evaluate the effectiveness of one or more control methods and to optimize parameters such as the water flow or exhaust flow by controlling the environmental sources of variability (e.g., wind speed, fixed work environment). The use of direct-reading instruments in order to obtain "before/after" measurements was also common in this type of study.

A major difference between the sub-databases in relation to the type of measurement involves the proportion of single measurements, which was much higher for the crystalline silica data for comparing exposure to an OEL based on occupation (83%) than for the data by task (29%). The vast majority of our occupation-related data originated either from the database of Flanagan et al. [8] (consisting only of single measurements) or from research reports of public organizations. For the latter, most of the documents provided detailed results in appendices for each of the samples collected during the study. For the analysis of task-related exposure levels, articles from scientific journals were the primary sources of the measurements, where results summarized in the form of tables are frequently used due to space constraints.

Compared to the database of Flanagan et al., our analyses covered a time period almost twice as long (1988–2007, compared to 1992–2002) and a wider range of tasks, occupations and source control methods. We estimate that approximately 47% and 64% of the exposure values from the analysis in relation to occupation were respectively shared with this source of crystalline silica and dust data; these proportions were much smaller for tasks, namely 2%.

4.2 Processing of the exposure data presented as summary parameters

The analyses performed on the crystalline silica exposure database represent the second application of the method allowing the reconstruction of the individual exposure values from the results presented in the scientific literature in the form of summary parameters. The formaldehyde exposure data documented by Lavoué et al. [27] contained a significant proportion of simulated concentrations, or 83% of the measurements in the ambient environment and 92% of the measurements in the breathing zone. These proportions were lower in our analyses for the two sub-databases containing the crystalline silica measurements, with 17% (occupations) and 71% (tasks). The variability in the GMs between the simulations in our analyses was relatively low with RSDs by category generally below 20%; only a few task categories had RSDs above 30%. The variability in the estimates by using 100 repetitions of the simulation procedure in our study was comparable to the variability obtained by Lavoué et al. which involved 1000 repetitions.

While validation of the simulation method is not one of our objectives, our results confirm that it allows literature exposure data reported in different formats to be used by means of statistical approaches usually reserved for individual measurements. In addition, the variability due to the probabilistic nature of the Monte Carlo simulation was relatively low, even with a moderate number of repetitions. Our results confirm the feasibility of the meta-analysis approach proposed by Lavoué et al. [27].

4.3 Statistical modeling of exposure levels

4.3.1 Overall results

The relatively low average value (22%) of the coefficient of determination of the most complete model for analyzing the crystalline silica data related to exposure during the work shift suggests that the occupation is not a very strong predictor of exposure levels. The average R^2 was, however, comparable to the coefficients of determination obtained in certain other analyses of occupational exposure databases, namely Flanagan et al. [8] (29%), Lavoué et al. [54] (29% for fixed effects) and Lavoué et al. [23] (21%).

In the case of the analysis in relation to the tasks performed, the model containing all the variables explained a much larger proportion of the variability in crystalline silica exposure levels, with an average of 60%. This proportion is comparable to numerous studies reviewed by Burstyn and Teschke [28] and suggests that exposure-related factors are relatively well defined by statistical modeling. The difference between the coefficients of determination obtained with the two analyses suggests that the nature of the task performed is much more closely associated with exposure than the occupation, mainly due to the number of different tasks that can be associated with the different categories of occupations. The task-based exposure assessment strategy allows a better identification of the preventive actions—including the use of source control methods for dusts—within the work shift. However, since the type and duration of performed tasks can vary from one day to the next, exposure assessment based on the occupational title remains an appropriate approach for estimating the health risk of a long-term exposure and for purposes of compliance with the limit values.

4.3.2 Effects of the exposure determinants

Sampling duration

A 50% increase in sampling duration was associated with a 10% to 19% reduction in crystalline silica exposure levels. The literature indicates that these downward trends may be due to the inclusion of periods without exposure, for example breaks and tasks or secondary processes, for the measurements associated with a longer sampling duration [52,55]. The inclusion of periods without exposure during sampling has in fact been reported in some sources of data in the task sub-database [56,57].

The effect of sampling duration was lower for respirable dust measurements, particularly for task-related data. One possible explanation could be that, in some cases, crystalline silica exposure is intermittent during the period sampled, while dust exposure can also occur during work involving materials that do not contain silica. The information contained in the database does not, however, allow this hypothesis to be verified.

Time trends

Analyses of the time trends in workplace exposure to chemical contaminants indicate that the levels have generally decreased over the last 50 years [58,59], mainly due to better control of the factors (e.g., administrative, economic or technological) associated with exposure [60]. This trend was observed in our analyses with an 11% reduction in crystalline silica levels per year for tasks, and 17% for regulatory compliance data in the analysis by occupation. However, in that analysis, the data associated with the surveillance strategy showed a 9% increase in the crystalline silica exposure levels per year. The different annual trends between the two sampling strategies for the analysis by occupation were also observed with the modeling of the respirable dust data. These discordant trends may be due to factors that were not included in the modeling process. The predictions were therefore made by taking the median value for the sampling year and, for the occupations, by giving an equal weight to the two sampling strategies in order to minimize the effects of the time trends on the estimates.

Source control methods

All the types of control methods present in the analysis of exposure levels based on tasks were associated with a reduction in crystalline silica concentrations, particularly local exhaust (69%) and the use of a wet process built into the tool (71%). The estimated effects for these two categories were slightly below those found in the studies—mostly experimental design studies—reviewed by Beaudry et al. [24]. This type of study generally involves control of the sources of environmental variability in order to adjust certain parameters (e.g., air/water flow rate, type of shroud or suction base) to obtain maximum efficiency for these devices. Our results therefore indicate that these different types of equipment remain very effective for reducing respirable crystalline silica concentrations under actual conditions of use while taking into account the simultaneous effects of other exposure determinants through modeling.

The industrial hygiene literature indicates that the selection of a control method is not based solely on its effectiveness, and that other factors must be taken into consideration, such as the compatibility with the tool, and the nature of the task performed—for example the use of water-based controls with electrical tools. Furthermore, control of respirable crystalline silica exposure is not restricted to technical methods, but also includes substitution and good work practices. The reader is invited to consult IRSST publication R-771 by Beaudry et al. for an exhaustive and detailed review of the general means of prevention and technical control methods specific to certain tools [24].

Other exposure-related factors

The effects related to the nature of the construction sites show that new construction projects are associated with lower exposure levels than renovation and demolition projects. It is likely that the degree of confinement is lower for new construction projects, with a larger proportion of activities being performed outdoors. Regarding the activity sector, residential construction sites were generally related to higher exposure levels in our analyses, compared to the Civil

Engineering and Roadwork reference category. Some features of this sector, mainly the significant proportion of self-employed workers and workers from small companies, where the resources dedicated to occupational health and safety are relatively less than in other sectors [61-63], may partially explain these results.

The use of control methods in the analysis of data for comparing the exposure to an OEL was evaluated in less detail than for tasks, due to the lack of information on the specific type used for a large proportion of the exposure data. The observed effects went in the expected direction, with lower exposure levels with the use of a control method and in an outdoor environment.

For the task analysis, the effects of the presence or absence of mechanical ventilation indoors and the impact of wind outdoors could be evaluated. The lowest exposure levels were related to the outdoor environment in the presence of significant wind, namely the reference category, while the absence of wind was associated with crystalline silica concentrations 38 times higher. The impact of wind on exposure was also identified by the study of Forest and Tremblay [10], with a reduction in the arithmetic mean of the respirable quartz concentration from 0.25 mg/m^3 to 0.05 mg/m^3 with a 30 km/h wind during the use of jackhammers. For the indoor environment, our results showed that exposure levels were 18 times higher in relation to the reference combination (outdoors/with wind), with and without general ventilation. The impact of ventilation on exposure was less significant indoors than outdoors. This observation for the indoor environment differs from the 66% reduction in crystalline silica exposure levels related to mechanical ventilation observed in an experimental study on surface grinding [64], and 25% for the use of jackhammers inside concrete mixers [65]. Considering the major contrasts between the effects for the combinations of the environment and ventilation variables, an equal distribution of the different circumstances was integrated into the predictions of the exposure levels by task.

4.3.3 Predictions of exposure levels by occupation and by task

Exposure by occupation

The fractions of exposures exceeding the ACGIH TLV (representing the probability of overexposure) by occupation, estimated from the respirable crystalline silica exposure levels standardized over eight hours, were much greater than the threshold of 5% generally deemed acceptable for the 11 categories studied. Thus, except for the "Other" category, the exceedance fractions by occupation were all greater than 50%—which represents at least one work shift out of two associated with overexposure. For the Québec TWAEV (0.1 mg/m^3), the exceedance fractions for these same occupations were above 30%. However, the estimated exceedance fractions did not take into account potentially different exposure variability between occupations, given that the same geometric standard deviation value was used for all the categories. The exceedance fractions calculated by using the GSDs estimated by category, presented in Table 5, gave similar results.

Our results indicate that the occupations of driller and underground worker are particularly at risk of overexposure, with standardized GMs for eight hours twice as high as the Québec standard and with exceedance fractions of 92%. The uncertainty about the estimation of exposure levels for drillers was relatively high since this category involved the smallest sample size, with 12 measurements. For underground workers, this group was identified as being the most at risk of overexposure during the first analysis of the database by Beaudry et al. [24]. These authors also noted that secondary exposure can be significant for this group, since the highest average levels were found for surveyors working near a tunneling machine.

The GMs predicted for cement finishers, bricklayer-masons and roofers were between 1 and 1.5 times the Québec standard. The database measurements for roofers sawing and installing concrete roof tiles are not representative of the exposure for this occupation in Québec since this type of roof is found only exceptionally in the province. The data for bricklayer-masons and cement finishers were associated with a range of varied tasks, some with a high exposure potential according to the literature, such as brick joint and surface grinding.

Exposure by task performed

Close to half of the estimated crystalline silica exposure levels for the tasks performed in relation to the developed prediction scenario were above the ACGIH threshold value; for six categories out of 27, they were above the Québec standard. It is important to note that these two limit values are based on an 8-hour shift. The comparison of exposure levels estimated for the tasks at these limit values nonetheless identifies the tasks most likely to contribute to the exposure over the work shift. For the most part, the estimations went in the expected direction, with tasks such as abrasive blasting, brick/stone joint grinding and tunnel boring among those generating the highest exposures. Furthermore, the levels predicted for material preparation activities and for cleaning were among the lowest.

Some of the tasks evaluated are associated with a single occupation according to the collective agreements governing the Québec construction industry. This is the case, for example, for brick joint grinding for the bricklayer-mason occupation, and tunnel boring for the underground worker occupation. The high estimated exposure levels for these tasks may explain to a large extent the average concentrations equal to or greater than the Québec standard predicted for an eight-hour shift. Furthermore, other occupations are associated with a wide range of types of work, particularly the occupations of pipeline, specialized and unskilled labourers. For example, the tasks associated with the pipeline labourer occupation include abrasive blasting as well as traffic control, which were associated with vastly different exposure levels. The 357 crystalline silica measurements for the specialized labourer occupation were associated with 15 task categories, of which 12 were represented in the analysis of exposure levels by task. The results obtained from the task analysis thus allow a clearer understanding of the observed exposure profiles for these occupations.

4.3.4 Comparison between crystalline silica and respirable dust exposure levels

The correlation between the GMs predicted for crystalline silica and dust was much higher for the task categories than for the occupations. This difference suggests that analysis of respirable dust levels may provide a rough indication of the distribution between the tasks most exposed and those less exposed to crystalline silica. However, the sanding, acoustic tile installation and shotcreting tasks had relatively low standardized crystalline silica levels compared to the predictions for respirable dusts. For the sanding task, 15 of the 31 measurements were associated with the "Gypsum and jointing material" category for the two contaminants and came from an

American publication [66]. Analysis of eight types of jointing compounds conducted in the framework of this study revealed the presence of traces of silica in two samples; furthermore, OSHA [67] recommends the use of jointing compounds without crystalline silica. For the shotcreting task, the damp nature of the material and the use of compressed air for this process would partly explain the differences between the predicted GMs by contaminant.

For the respirable crystalline silica percentages calculated for 924 samples, the median value (11%) was comparable to the average of 12% based on 68 measurements in the study of Tjoe Nij et al. [68]. The differences between the median percentages by category for the five studied variables were relatively low, varying between 5% and 15% for the majority of categories. The contrasts were markedly greater between the different categories of materials, where the medians varied between 2% (acoustic tiles) and 19% (sand). The high percentage for sand was very likely related to the geological composition of this material, with a high quartz content. Literature data indicate that the crystalline silica content of respirable dusts is generally lower than that of the raw material or deposited dusts [1,69,70], which complicates the prediction of silica concentrations based on the nature of the material. The relationship between the crystalline silica percentages in the respirable dust samples and the silica content of this bulk material was not evaluated in our analyses since information on the results of the analysis of the material's composition was not available for the vast majority of the measurements.

For the measurements relating to roofers (the occupation with the highest median percentage), the median value of 17% was similar to the results for the analysis of the silica content of the dust deposits from concrete tiles associated with these measurements in the database, which varied between 17% and 26%, depending on the study. The crystalline silica content of the dusts was also relatively high for diamond cutting of concrete and asphalt, with 15%, and may be due in part to the environmental conditions in which roadwork projects are usually carried out (dry and hot conditions) [8]. Stratification of the results for this category by control method indicates that the percentage is in fact lower with spraying built into the road-milling machine (6%, n=19) compared to the absence of a control method (28%, n=28).

While major contrasts were observed between the medians of the respirable crystalline silica percentages for the determinant categories studied, the variability in the percentages found within the same category was significant for the majority of them. This variability suggests that gravimetric measurements of dusts have a relatively limited usefulness in the environmental surveillance of silica exposure in the construction industry. The use of the 90th centile of the distribution of the percentages by category, presented in Appendix 5, combined with the respirable dust concentrations, could nevertheless provide an indication of the crystalline silica exposure levels while taking into account the uncertainty associated with the wide variability in dust composition observed in our results.

Finally, the crystalline silica content of the dusts and their concentrations are only two of the factors associated with the development of harmful respiratory health effects, particularly for particles whose size is close to nanometric scale. Among them, we should mention the surface reactivity and morphology of the particles, as well as the interaction between crystalline silica and other substances in the dusts [71,72]. However, these parameters have not been extensively studied in the context of the construction industry: only two sources in the database (out of 115) also characterized the morphology of the dusts by electron microscopy [68,73]. Moreover, a recent study quantified such parameters as the number, mass and distribution of nanometric scale particles during the preparation of asphalt and concrete in a laboratory [74]. Considering the advancement in knowledge about the toxicity of ultrafine particles (UFPs) containing silica, and the development of measuring instruments, research on the specific characterization of the exposure of construction workers to this type of particle is to be expected in the near future.

4.4 Limitations

4.4.1 Limitations related to the lack of documentation on exposure-related factors

The use of occupational exposure data from the literature presented numerous challenges regarding the analysis and interpretation of results during this study. Among these, the descriptions of parameters such as the use of control methods, the work environment, and the type of project and construction site were missing for approximately 33% of the task-related crystalline silica measurements, and for 66% of the measurements in the analysis by occupation. These proportions would have been even higher without the restriction to the lines of data where the occupation or the task and the sampling duration were available, and where the quality of the information on the determinants and analysis were at a minimum acceptable. Some parameters potentially related to exposure, such as the bulk material's silica content and the presence of a secondary source of exposure, were too inadequately documented to be included in the modeling process. The impact of the work environment variable on the exposure levels could only be evaluated according to an outdoors/indoors dichotomy, thus eliminating the distinction between enclosed, confined and closed spaces due to the insufficient sample sizes for some of these categories. It is likely that certain measurements associated with the "not specified" category were taken in these environments, and a more detailed analysis would have been made possible by a more rigorous documentation of this parameter in the data sources. The variable related to the dust control methods for the analysis of exposure levels by occupation also had to be limited to a "with" or "without" control method dichotomy for this very same reason.

The issue of missing descriptive parameters associated with exposure levels has also been reported for occupational exposure databases such as IMIS[8] [75-77] as well as for articles from scientific journals [78-80]. Methods based on multiple imputation [81] have been used successfully for more than 30 years in the social and medical sciences and in economics [82] to overcome the difficulties related to the analysis of sets of data consisting of missing information for the variables of interest. Multiple imputation was recently applied in the field of occupational hygiene to account for non-detected concentrations [83], but to our knowledge, this is not yet the case for addressing the missing description of exposure-related factors. Application of these methods to the database analyses would provide more detailed conclusions about the factors contributing to crystalline silica exposure on construction sites, in particular for exposure during the work shift in relation to the occupation.

[8] Integrated Management Information System: Database containing sampling results produced by OSHA

4.4.2 Limitations related to the representativeness and distribution of exposure data

Even though the database contains the majority of crystalline silica exposure data associated with construction activities reported in the literature during the last two decades, some exposure-related circumstances remained under-represented. For example, the occupation of driller and the task of bush hammering concrete, which had the highest predicted crystalline silica exposure levels in their respective analyses, also had the smallest sample sizes with 12 measurements each. The small number of measurements for these categories increases the uncertainty associated with the results, and in the case of bush hammering of concrete, the very short median sampling duration (5 minutes) compared to the other tasks complicates the interpretation of the exposure levels observed for this task. Also, only 2% of the evaluation measurements for specific tasks came from the residential sector, which accounts for more than one-third of the employees working in the Québec construction industry [84]. Furthermore, certain working conditions encountered in the analyses are perhaps not necessarily representative of those present on Québec construction sites, for example the exposure data on roofers mentioned in the previous section.

One of the major limitations encountered in the analysis of task-related exposure levels was the very unequal distribution of data between the categories of the different variables. The strong association between the task performed and the categories of tools and materials prevented the inclusion of these three variables separately in the modeling process. This strong association results in part from the very nature of the task; for example, brick joint grinding involves almost exclusively the use of a brick joint grinder. The inclusion of strongly associated variables in a model may cause colinearity problems which increase the uncertainty associated with the estimation of effects. In the same way as the problems related to the lack of documentation on certain parameters in the database, the unequal distribution of data limited the number and type of variables included in the modeling process.

Finally, the exposure data originating from the literature and government databases are collected for different reasons and do not necessarily represent a random and representative sample of the population studied. An analysis presented by Lavoué [85] of the potential biases associated with the sources of exposure measurements reveals that they can be related to the selection of the evaluated workplaces and to the sampling strategy, among others. The use of "mixed" effects regression models, using the source of data (publication) as a random effect, allowing the heterogeneity in the designs and conditions between the studies to be taken into account, and the potential correlation of the measurements originating from the same study, is an approach indicated for the analysis of literature data [86,87]. This type of model was not used in our analyses because the results for certain combinations of variables came from a single source of data. Similar difficulties related to the inclusion of the source of data as a random effect were identified by Hein et al. during the statistical modeling of occupational exposures (taken from the literature) to aromatic hydrocarbons and chlorinated solvents [29,88]. The separate analysis of the evaluation of the exposure by specific task and by work shift (in relation to the occupation) and, for the latter, the distinction between the regulatory compliance strategy and the other strategies for the measurements for a work shift nevertheless partly compensated for this problem. The importance of the strategy variable in this analysis suggests a marked difference between the data originating from inspections and those without regulatory significance. This situation may be due to the approach favoured by American inspectors who tend to target situations that appear to be non-compliant with the standards [89,90], contrary to other measurement strategies. The average exposures for the occupations for eight hours were therefore estimated by giving an equal share to the effects related to the two sampling strategies.

5. CONCLUSION

Operations and working conditions change continually from one construction site to another, which complicates the risk-anticipation and prevention process related to silica exposure in this industry. This may lead to an underestimation of the frequency and intensity of the silica-containing dust exposure for construction workers. The use of literature data, despite certain limitations, is a rather efficient approach by which exposure-related factors can be characterized in many circumstances.

In this work, the integration of published exposure data allowed the development of predictive exposure models in relation to the occupations and the tasks performed, by taking into account workplace characteristics. Multimodel inference identified the determinants with the most impact on the exposure levels and quantified their effects. In particular, the estimated effectiveness rates for the source control methods were as high as 71% (for spraying devices built into the tool), after accounting for the task performed, the sampling duration, and other exposure-related variables. Our results also indicate that the variability associated with the estimation of the geometric means and model parameters from the Monte-Carlo method is relatively small, by using a moderate number of repetitions.

According to our estimates, the exposure levels for an eight-hour work shift exceed the ACGIH value and the Québec regulatory standard with a frequency much greater than the threshold that is generally considered acceptable, suggesting that the majority of the workers in this industry are at risk of developing occupational diseases related to crystalline silica over the long term. With the models developed from measurements aiming to evaluate exposure on the basis of the tasks performed, it is possible to identify the activities that have the greatest impact on the levels and to implement control measures. However, the technical source control methods for dusts do not necessarily reduce the exposure to acceptable levels for the most polluting tasks. Our results indicate that the use of appropriate respiratory protection is necessary for these tasks in order to protect workers against the occupational diseases related to crystalline silica. The results of the statistical modeling of respirable dust measurements were comparable to those obtained for crystalline silica measurements in relation to the exposure levels by occupation and by task. Nonetheless, it remains difficult to predict silica concentrations from the sampled dusts due to a large variability in the crystalline silica percentages by category of materials, tools, occupations and tasks, despite marked average differences between the categories. Finally, continued quantitative exposure monitoring is necessary to make up for the gaps in knowledge on the impact of certain determinants on crystalline silica concentrations, and to follow the evolution in time trends, among others.

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APPENDICES

APPENDIX 1. ESTIMATED PARAMETERS FOR EXPOSURE IN A WORK SHIFT

	Crystalline silica			Dusts		
Variable	**β[A]**	**SE[B]**	**RSD[C] (%)**	**β[D]**	**SE**	**RSD (%)**
Intercept	-2.185	0.967	3	-0.016	1.001	335
Duration (ln(min))	-0.261	0.150	4	-0.195	0.149	4
Year (-1991)	0.083	0.034	2	0.058	0.043	3
Occupation						
Other	-0.975	0.271	1	-0.317	0.193	1
Bricklayer-mason	0.530	0.154	3	0.536	0.149	0
Boilermaker				-2.052	0.588	6
Cement finisher	0.815	0.168	5	0.890	0.175	0
Foreman	-0.206	0.464	29			
Roofer	0.989	0.703	3	0.260	0.621	4
Driller	1.809	0.499	0	1.292	0.516	0
Labourer (unskilled)	-0.054	0.162	37	-0.029	0.162	5
Pipeline labourer	0.030	0.243	28	0.847	0.232	0
Specialized labourer	Reference			Reference		
Heavy equipment operator	-0.274	0.192	4	-0.459	0.183	3
Underground worker	1.264	0.370	3			
Activity sector						
Civil engineering and roadwork	Reference			Reference		
Industrial, institutional and commercial	0.628	0.270	2	0.374	0.212	2
Residential	0.379	0.374	7	0.302	0.611	2
Not specified	0.629	0.281	2	-0.123	0.184	1
Project type						
New construction	-0.593	0.316	4			
Demolition	0.071	0.248	25			
Renovation	Reference					
Not specified	-0.598	0.581	3			

	Crystalline silica			Dusts		
Variable	**β[A]**	**SE[B]**	**RSD[C] (%)**	**β[D]**	**SE**	**RSD (%)**
Sampling strategy						
Regulatory compliance	2.684	0.913	2	0.815	0.937	5
Surveillance	Reference			Reference		
Environment						
Outdoors	Reference			Reference		
Indoors	0.177	0.321	11	1.339	0.348	1
Not specified	0.310	0.636	7	0.528	0.472	1
Control (use)						
No	Reference			Reference		
Yes	-0.173	0.187	11	-0.236	0.211	8
Not specified	0.018	0.268	55	0.054	0.211	9
Duration/Strategy interaction						
Duration (ln(min)): Compliance	-0.036	0.140	19	0.016	0.127	38
Year/Strategy interaction						
Year (-1991)/Compliance	-0.271	0.046	1	-0.078	0.061	2
Environment/Control interaction						
Indoors/With control	-0.021	0.156	38			
Indoors/Not specified	0.079	0.504	5			
Not specified/With control	-0.164	0.625	11			
Not specified/Not specified	-0.061	0.431	14			

[A] Weighted estimate for 260 models, average of the 20 repetitions
[B] Unconditional standard error, average of the 20 repetitions
[C] Relative standard deviation of the weighted estimate for the 20 repetitions
[D] Weighted estimate for 104 models, average of the 20 repetitions

APPENDIX 2. ESTIMATED PARAMETERS FOR EXPOSURE BY TASK PERFORMED

	Crystalline silica			Dusts		
Variable	**β[A]**	**SE[B]**	**RSD[C] (%)**	**β**	**SE**	**RSD (%)**
Intercept	-1.23	0.569	14	-0.832	0.454	14
Duration (ln(min))	-0.513	0.092	5	-0.041	0.070	38
Year (-1988)	-0.112	0.025	11	-0.009	0.018	58
Task						
Spraying				-1.66	0.446	18
Other masonry-related tasks	-2.32	0.432	8	-0.948	0.373	18
Other roadwork	-2.09	0.266	10	-1.77	0.251	7
Bush hammering concrete	0.667	0.587	23	0.248	0.615	52
Breaking - Other tools	-0.168	0.365	66	-0.723	0.360	12
Breaking - Jackhammer	0.668	0.312	13	-0.013	0.299	1391
Breaking - Multiple tools (including jackhammers/percussion drills)	2.37	0.357	7	1.20	0.314	12
Heavy equipment operation				-1.21	0.342	30
Diamond cutting of concrete or asphalt	0.656	0.421	19	-0.414	0.533	52
Abrasive blasting	1.42	0.380	22	1.33	0.345	25
Demolition	-0.809	0.295	37	-1.12	0.258	26
Manual moving of small rocks, soil, etc.	-1.34	0.498	12			
Mechanized moving or rocks, soil, etc.	-1.09	0.453	17	-1.02	0.269	11
Tunnel boring	1.25	0.264	12	-0.002	0.231	5002
Installation of acoustic ceiling tiles	-1.64	0.295	19	0.273	0.301	97
Mixing of cements and mortars	-2.44	0.328	9	-0.784	0.282	25
Brick/stone joint grinding	1.35	0.294	8	0.017	0.366	1191
Surface grinding	Reference			Reference		
Installation of concrete formwork	-0.996	0.173	13	-0.678	0.152	13
Cleaning	-2.38	0.446	15	-1.56	0.408	19
Drilling - concrete	-0.270	0.328	99	-0.527	0.341	40

Variable	Crystalline silica			Dusts		
	β[A]	SE[B]	RSD[C] (%)	β	SE	RSD (%)
Task (cont.)						
Drilling - stone	-0.921	0.207	18	-0.643	0.181	17
Piercing - ground and stone	-1.69	0.411	23	-1.94	0.304	12
Sanding	-1.32	0.394	15	0.093	0.349	97
Shotcreting	-0.859	0.328	20	-0.266	0.280	57
Sawing masonry	-0.315	0.285	34	-0.311	0.271	37
Foundation work	-2.01	0.249	13	-1.53	0.233	10
Electrical maintenance work	-1.84	0.273	9	-0.967	0.239	16
Excavation work	-2.17	0.267	11	-1.14	0.218	8
Source control method						
Spraying/tool	-1.24	0.318	6	-2.09	0.329	5
Spraying/surface + source isolation				0.498	0.246	29
Spraying/surface	-0.847	0.310	25	-2.82	0.397	9
Local exhaust	-1.17	0.182	5	-1.67	0.167	9
None	Reference			Reference		
Other/Not specified	0.140	0.381	63	-0.787	0.328	14
Activity sector						
Civil engineering and roadwork	Reference			Reference		
Industrial, institutional and commercial	-0.574	0.268	12	-0.265	0.253	61
Residential	0.238	0.409	36	-0.772	0.494	27
Other/Not specified	1.74	0.299	9	0.557	0.513	27
Project type						
New construction	Reference			Reference		
Renovation	-0.093	0.260	107	0.954	0.389	21
Other/Not specified	-0.813	0.340	23	0.671	0.540	21

Variable	Crystalline silica			Dusts		
	β[A]	SE[B]	RSD[C] (%)	β	SE	RSD (%)
Environment						
Outdoors	Reference			Reference		
Indoors	2.87	0.197	5	1.77	0.166	4
Not specified	1.19	1.406	12	0.663	1.231	13
Ventilation						
No	3.63	0.251	3	2.18	0.254	5
Yes	Reference			Reference		
Not specified	2.32	0.408	6	1.46	0.337	7
Environment/Ventilation interaction						
Indoors/Without ventilation	-3.61	0.303	4	-1.52	0.330	13
Indoors/Not specified	-4.10	0.349	4	-1.15	0.289	8
Not specified/Without ventilation	-2.72	1.447	8	-1.76	0.923	13
Not specified/Not specified	-0.971	1.412	15	-1.17	0.900	13

[A] Weighted estimate for 80 models, average of the 20 repetitions
[B] Unconditional standard error, average of the 20 repetitions
[C] Relative standard deviation of the weighted estimate for the 20 repetitions

APPENDIX 3. RESPIRABLE CRYSTALLINE SILICA PERCENTAGES ASSOCIATED WITH OCCUPATIONS, TASKS, TOOLS, MATERIALS AND CONTROL METHODS

	n[A]	nE[B]	P10[C]	P25[D]	Med[E]	P75[F]	P90[G]
Occupation							
Roofer	61	4	10%	13%	17%	24%	48%
Heavy equipment operator	143	14	3%	6%	12%	24%	35%
Driller	13	3	10%	11%	12%	15%	17%
Specialized labourer	254	22	3%	7%	11%	15%	22%
Labourer (unskilled)	86	6	3%	7%	10%	16%	23%
Cement finisher	94	8	3%	6%	9%	14%	20%
Bricklayer-mason	172	10	4%	6%	9%	14%	19%
Other	35	8	2%	3%	9%	15%	29%
Underground worker	20	3	2%	4%	5%	16%	19%
Pipeline labourer	46	6	1%	3%	4%	15%	22%
Tasks							
Sawing roofing	39	4	11%	13%	17%	25%	50%
Installation and attachment of roof parts	22	3	5%	14%	16%	24%	28%
Diamond cutting of concrete or asphalt	98	7	5%	7%	15%	28%	38%
Support for bricklayer-mason	13	1	4%	7%	15%	18%	21%
Mechanized moving or rocks, soil, etc.	17	3	3%	4%	14%	25%	33%
Not specified	105	1	3%	6%	14%	19%	23%
Sawing masonry	74	11	5%	7%	12%	19%	23%
Breaking pieces of masonry	83	10	7%	9%	12%	14%	18%
Multiple tasks	21	7	2%	4%	12%	13%	14%
Sawing – Other	14	1	7%	10%	12%	13%	28%
Drilling masonry	48	7	5%	7%	11%	16%	24%
Brick/stone joint grinding	108	5	5%	7%	9%	13%	18%
Surface grinding	63	6	5%	6%	9%	12%	14%
Cleaning	16	2	5%	7%	8%	11%	19%
Other tasks	43	10	4%	6%	8%	12%	21%
Demolition	49	4	2%	3%	7%	9%	13%
Tunnel boring	11	3	1%	3%	7%	17%	19%
Abrasive blasting	37	6	2%	3%	5%	18%	22%
Sanding	17	2	2%	2%	5%	16%	21%
Shotcreting	17	2	1%	2%	3%	4%	4%
Mixing of cements and mortars	17	5	1%	1%	3%	6%	16%
Roadwork - Other	12	3	2%	2%	3%	16%	18%

	n[A]	nE[B]	P10[C]	P25[D]	Med[E]	P75[F]	P90[G]
Tool							
Other (mechanical tools)	35	6	3%	6%	16%	27%	50%
Road-milling machine	98	7	5%	7%	15%	28%	38%
Percussion drill	27	5	6%	12%	14%	15%	21%
Portable masonry saw	50	10	7%	11%	14%	19%	27%
Not specified	263	12	3%	5%	13%	19%	24%
Tunneling machine	14	4	10%	11%	12%	16%	17%
Portable saw	13	1	7%	10%	12%	12%	26%
Drill	20	3	7%	7%	12%	23%	25%
Multiple tools	16	8	2%	3%	12%	14%	17%
Walk-behind concrete saw	8	4	5%	8%	12%	20%	27%
None	6	2	3%	6%	11%	20%	32%
Brick/stone joint grinder	109	5	5%	7%	9%	13%	18%
Surface finishing grinder	64	7	5%	7%	9%	12%	15%
Jackhammer	81	4	4%	7%	9%	12%	14%
Broom, shovel, squeegee and blower	16	4	5%	7%	8%	17%	20%
Masonry saw bench	20	3	5%	6%	7%	11%	15%
Abrasive blasting machine	31	4	2%	3%	5%	19%	22%
Tunneling machine	7	2	1%	2%	4%	7%	7%
Heavy equipment (Backhoe/excavator/bulldozer/ bucket loader/mechanical digger)	21	7	2%	3%	4%	11%	15%
Mortar or cement mixer	8	2	1%	1%	3%	5%	6%
Other (inert tools)	17	6	2%	2%	3%	4%	9%
Material							
Sand	20	2	3%	9%	19%	23%	34%
Asphalt	93	5	5%	6%	17%	28%	38%
Brick	7	4	5%	6%	15%	37%	61%
Cement roofing tile	50	3	10%	13%	15%	23%	28%
Various materials-2 (containing concrete)	78	6	5%	7%	12%	19%	23%
Concrete	190	20	5%	8%	12%	14%	19%
Not specified	250	2	3%	6%	9%	16%	22%
Mortar	115	6	4%	6%	9%	13%	18%
Other	19	6	2%	5%	7%	16%	27%
Stone	35	5	1%	2%	4%	7%	11%
Various materials-1 (containing sand)	57	6	2%	3%	4%	13%	21%
Acoustic tiles	10	1	1%	2%	2%	2%	3%

	n[A]	nE[B]	P10[C]	P25[D]	Med[E]	P75[F]	P90[G]
Source control							
Other	13	3	9%	17%	26%	33%	45%
None	234	28	3%	7%	12%	16%	34%
Local exhaust	117	14	6%	8%	11%	15%	23%
Not specified	458	8	3%	5%	9%	17%	23%
Local exhaust + Spraying/surface	18	2	2%	3%	9%	18%	24%
Spraying/surface	47	8	2%	3%	8%	15%	22%
Spraying/tool	37	8	5%	6%	8%	12%	16%

[A]: Total of the individual exposure values
[B]: Number of sources from which the exposure values were taken
[C]: 10th centile of the distribution
[D]: 25th centile of the distribution
[E]: Median value
[F]: 75th centile of the distribution
[G]: 90th centile of the distribution

APPENDIX 4. EXAMPLE OF THE CALCULATION OF THE PREDICTION OF A GEOMETRIC MEAN

As mentioned in section 2.2.3, it is possible to make predictions of the geometric means for various scenarios of interest from the weighted estimates presented in Appendices 3 and 4. The following example presents the calculation of a prediction of the geometric mean of the crystalline silica exposure for 8 hours for the occupation of heavy equipment operator according to the following scenario:

Variable	Category or numerical value
Occupation	Heavy equipment operator
Sampling duration	480 minutes
Year	2000
Activity sector	Civil engineering and roadwork
Project type	New construction
Environment	Outdoors
Control	No
Strategy	Equal part compliance and surveillance

The table below contains the weighted estimates (from Appendix 3) for the categories corresponding to the scenario in Column A. The values—or multiplicative factors—associated with the prediction scenario are entered in Column B. For each nominal variable, the sum of the values of the categories varies between 0 and 1. For the reference categories, the value for the scenario is entered between parentheses and is not part of the calculation since its estimate is contained in the constant.

Column	*A*	*B*	*C*
	β	**Scenario**	**A x B**
Constant	-2.185	1	-2.185
Duration (ln(min))	-0.261	ln(480)	-1.611
Year (-1991)	0.083	2000-1991	0.747
Occupation			
Heavy equipment operator	-0.274	1	-0.274
Activity sector			
Civil engineering and roadwork	Reference	(1)	0
Project type			
New construction	-0.593	1	-0.593
Sampling strategy			
Regulatory compliance	2.684	1/2	1.342
Surveillance	Reference	(1/2)	0
Environment			
Outdoors	Reference	(1)	0

Column	*A*	*B*	*C*
	β	**Scenario**	**A x B**
Control (use)			
No	Reference	(1)	0
Duration/Strategy interaction			
Duration (ln(min)): Compliance	-0.036	1/2 x ln(480)	-0.110
Year/Strategy interaction			
Year (-1991)/Compliance	-0.271	1/2 x (2000-1999)	-0.135

The prediction is first calculated by multiplying the weighted estimator by category by the value of the scenario, as illustrated in Column C. The sum of the values in Column C (-2.819) represents the natural logarithm of the predicted geometric mean; the exponential of this value represents the prediction of the GM in mg/m^3, or 0.06 mg/m^3. It should be noted that the uncertainty associated with the prediction cannot be directly obtained using this approach.