Determinants of Respirable Crystalline Silica Exposure Among Stoneworkers Involved in Stone Restoration Work

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Received 21 May 2013; in final form 4 July 2013; accepted 8 July 2013

ABSTRACT

Objectives: Crystalline silica occurs as a significant component of many traditional materials used in restoration stonework, and stoneworkers who work with these materials are potentially exposed to stone dust containing respirable crystalline silica (RCS). Exposure to RCS can result in the development of a range of adverse health effects, including silicosis and lung cancer. An understanding of the determinants of RCS exposure is important for selecting appropriate exposure controls and in preventing occupational diseases. The objectives of this study were to quantify the RCS exposure of stoneworkers involved in the restoration and maintenance of heritage properties and to identify the main determinants of RCS exposure among this occupational group.

Methods: An exposure assessment was carried out over a 3-year period amongst a group of stone-handlers involved in the restoration and maintenance of heritage buildings in Ireland. Personal air samples (n = 103) with corresponding contextual information were collected. Exposure data were analysed using mixed-effects modelling to investigate determinants of RCS exposure and their contribution to the individual’s mean exposure. Between-depot, between-worker, and within-worker variance components were also investigated.

Results: The geometric mean (GM) RCS exposure concentrations for all tasks measured ranged from <0.02 to 0.70 mg m⁻³. GM RCS exposure concentrations for work involving limestone and lime mortar were <0.02–0.01 mg m⁻³, tasks involving granite were 0.01–0.06 mg m⁻³, and tasks involving sandstone were <0.02–0.70 mg m⁻³. Sixty-seven percent of the 8-h time-weighted average (TWA) exposure measurements for tasks involving sandstone exceeded the Scientific Committee on Occupational Exposure Limits recommended occupational exposure limit value of 0.05 mg m⁻³. Highest RCS exposure values were recorded for the tasks of grinding (GM = 0.70 mg m⁻³) and cutting (GM = 0.70 mg m⁻³) sandstone. In the mixed-effects analyses, task was found to be significantly associated with RCS exposure, with the tasks of grinding and cutting resulting in average exposures of between 32 and 70 times the exposures recorded for the task of stone decorating. The between-depot, between-worker, and within-worker variance components were reduced by 46, 89, and 49%, respectively, after including task in the mixed effects model.
**Conclusions:** Restoration stoneworkers are regularly overexposed (compared with 0.1 and 0.05 mg m$^{-3}$ 8-h TWA) to RCS dust when working with sandstone. The results indicate that the tasks of cutting and grinding sandstone are predictors of increased exposure to RCS dust. In order to decrease exposure to RCS, efforts should be focused on developing and implementing interventions which focus on these high-risk tasks.

**KEYWORDS:** determinants of exposure; exposure assessment; silica exposure

**INTRODUCTION**
Crystalline silica is an abundant mineral in the Earth’s crust and is present in varying amounts in almost all rocks, clays, and sands. Exposure to respirable crystalline silica (RCS) is therefore possible when these materials are worked and can lead to a range of adverse health effects depending on the magnitude of exposure. The most widely reported health effect associated with exposure to RCS is silicosis (Landrigan et al., 1986; Rosenman et al., 1996; NIOSH, 1999; Forastiere et al., 2002). Other health effects include lung cancer (IARC 1997; Siemiatycki et al., 1989), stomach cancer (Siemiatycki et al., 1989), a range of autoimmune diseases such as systemic sclerosis (Sluis-Cremer et al., 1985; Englert et al., 2000), rheumatoid arthritis (Stolt et al., 2005), chronic and subclinical renal disease (Steenland et al., 1990, 1992; Hotz et al., 1995; Steenland and Goldsmith, 1995), and cardiovascular diseases (Chen et al., 2012). There is also evidence that workers exposed to silica are at an increased risk of mycobacterial infections of the lungs (Corbett et al., 1999) and chronic obstructive pulmonary disease (Oxman et al., 1993).

Workplace exposure to RCS is well documented in many industries including construction (Pannell and Grogin, 2000; Lumens and Spee, 2001; García et al., 2006; Heitbrink and Bennett, 2006; Echt and Sieber, 2007; Miscetti et al., 2011; Middaugh et al., 2012), roofing manufacture (Fayerweather et al., 2011), the heavy clay industry (Love et al., 1999), potteries (Cherry et al., 1998), the industrial silica sand industry (Brown and Rushton, 2005), agriculture (Archer et al., 2002; Swanepoel et al., 2011), exploration of natural resources (hydraulic fracking; Napoli, 2012), and construction stone masonry (Guénél et al., 1989; Tharr and Lofgren, 1993; Cain, 2009; HSE, 2009). However, few studies (Seaton and Cherrie, 1998; HSE, 2009) have evaluated personal RCS exposure among restoration stoneworkers working with high silica content materials such as sandstone.

Restoration stone masonry can be distinguished from construction stone masonry by the use of tools and techniques specific to restoration work (Caroe and Caroe, 2001; English Heritage, 2012). Their work regularly involves the application of fine decorative detail to stone, which often requires the worker to work in very close proximity to the exposure source. Restoration stoneworkers are also required to follow strict conservation guidelines and therefore not permitted to substitute high silica content materials with low silica alternatives. Sandstone was widely used in Europe as a construction material down through the centuries. In Ireland, the Normans (11–12th century) regularly used sandstone for dressings and carvings as it was easily quarried and a highly favoured building material. It has been used for centuries in roofing, flooring, and the construction of dry stone walls. In the restoration of these buildings today, it is common architectural practice to use the stone from the quarry which supplied the original stone, or a stone with similar properties (Galán et al., 1999; Fitzner et al., 2003; Bolton, 2006; Steinbauer et al., 2012).

Sandstone is a sedimentary rock with an average quartz content of 82% (w/w) or higher (Carmichael, 1989; Kissane and Pavia, 2008). Airborne RCS concentrations are related to the quartz content of the rock being worked (Guénél et al., 1989; Kullman et al., 1995) and therefore stoneworkers carrying out work on sandstone are potentially exposed to excessive levels of RCS. Research by Seaton and Cherrie (1998) on workers involved in the restoration of a sandstone cathedral in Scotland and the UK baseline silica survey (HSE, 2009) suggest that RCS exposure for this occupational group could regularly be in excess of the workplace exposure limit in the UK of 0.1 mg m$^{-3}$. Furthermore, the findings of the UK’s baseline survey on RCS exposure suggest that engineering controls are often absent or inadequate for this type of work. A pilot study investigating RCS exposures among restoration stoneworkers (Healy et al., 2013) found high exposures to RCS were frequently experienced.
by this group. This warrants a more detailed investigation of RCS exposures in this group particularly for high-exposure tasks. The further characterization of the RCS exposures for this occupational group is imperative in order to design an effective approach to control exposure to RCS. Knowledge of the main determinants of RCS exposure will aid the design of an effective approach to control exposure to RCS in restoration stonework. Previous studies found that material worked on, task, equipment, trade, job site, work area (indoors/outdoors), cross draft, and engineering controls to be important determinants of RCS exposure in the construction sector (Lumens and Spee, 2001; Bakke et al., 2002; Flanagan et al., 2006; Sauvé et al., 2012). The objectives of this study were to characterize the RCS exposures of stoneworkers involved in the restoration of historical monuments in Ireland and to identify workplace determinants of RCS exposure. These results will be used to develop effective workplace intervention strategies to reduce high-RCS-exposure tasks during restoration activities.

MATERIALS AND METHODS

Study population and site description
The study population consisted of 35 restoration stoneworkers employed with the Commissioners of Public Works Ireland, responsible for managing, maintaining, and restoring over 740 of Ireland’s national monuments. Worker participation was voluntary, and subjects were recruited in coordination with the organization’s Health and Safety unit and depot managers. The stoneworkers were located in six centralized depots and associated historic monuments around Ireland. During this study, workers worked on sandstone, limestone, lime mortar, and granite. The tasks carried out and the materials used in a depot at any one time were dependent on the materials and the type of restoration required for the monument under restoration. Minor restoration of a monument only involved repointing, but major restoration required restoration and/or construction of existing or new sections of the monument. The stoneworkers worked in a stone cutting workshop located in the depot or on site at the monument under restoration depending on the task they were carrying out. Within the group restoration stoneworkers, two main job titles could be distinguished based on their job specifications: stone cutter and stonemason (Table 1). Each depot had an average of one stone cutter and seven stonemasons (range: 1–17).

Table 1. Description of job specifications of stoneworkers included in study

<table>
<thead>
<tr>
<th>Job title</th>
<th>Job specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone cutter</td>
<td>A stone cutter specialises in cutting stone. The majority of stone cutting is carried out in a workshop. In the workshop, this involves cutting quarried stone to the rough size required for the finished piece, using a water cooled primary saw. If further significant cutting is required on site, a stonecutter uses a 5”, 9”, or 12” angle grinder.</td>
</tr>
<tr>
<td>Stonemason</td>
<td>A stonemason performs several tasks including the shaping of stone to the exact geometrical shape required for the finished piece, normally using a 5” angle grinder, addition of decorative detail to the finished pieces with hand and pneumatic chisels, arranging the resulting finished pieces in the monument and removing deteriorated mortar from a monument before repointing with new mortar. A stonemason carries out the majority of his work on site and rarely in the workshop.</td>
</tr>
</tbody>
</table>
Sheet for field sampling. This field sheet was used to collect detailed contextual information during the measurement period including details about the task, tools, materials, exposure controls, respiratory protective equipment (RPE) and other information the author deemed important to record.

At the beginning of the study, a visual assessment was carried out in each of the stone cutting workshops using a checklist to collect detailed information on exposure controls used. This checklist was developed with reference to similar studies (HSE, 2006; Renton et al., 2010) and collected information on the following: design of local exhaust ventilation (LEV) system, maintenance and effectiveness of the LEV including capture velocity, worker use of LEV and RPE, and cleaning and housekeeping practices.

Sampling methodology
Samples were collected using an air sampling pump (Sidekick pump; SKC Ltd, Dorset, UK.) with Higgins Dewell cyclone (Casella, Bedford, UK.) and 25 mm, 5 µm pore size polyvinyl chloride filters pre-calibrated to a flow rate of 2.2 l min \(^{-1}\) with a primary air flow meter (DryCal DC Lite; BIOS International, NJ, USA). The sampling pump was attached to a belt around the waist or to a harness. The cyclones were attached to the worker’s lapel within 30 cm of his breathing zone, ensuring the cyclone inlet was in a downward vertical position. Workers were asked to perform their work tasks as normal to ensure that the dust levels measured were representative of normal work activities. This included normal use of all tools, engineering controls, and RPE. Task sampling was performed, and when sampling a work task, all preparatory work i.e. marking out of stone, positioning of stone, the work task, and all clean-up activities after the task were monitored. Workers typically only performed one single task per work shift.

The respirable dust samples were analysed gravimetrically according to HSE MDHS 14/3, and the RCS content on the filter was quantified by X-ray diffraction as per HSE MDHS 101. All laboratory analytical analysis was carried out by the Institute of Occupational Medicine in Edinburgh. Samples below the analytical limit of detection (LOD) for crystalline silica were reported as <0.02 mg.

In addition, real-time dust measurements were carried out using a SidePak AMS10 personal aerosol monitor (TSI Incorporated, Shoreview, MN, USA) adjusted to measure respirable dust using a 10 mm Dorr-Oliver cyclone attachment. The SidePak AMS10 was calibrated to the recommended flow rate of 1.7 l min \(^{-1}\) using a primary air flow meter (DryCal DC Lite; BIOS International, NJ, USA.) and was set to log data at 1-min intervals. The data were downloaded to a computer using TSI Trackpro software. Results of the SidePak were used to examine exposure patterns whilst different tasks were carried out and to identify tools and tasks which created high levels of dust.

Statistical analysis
Task-specific exposure data were expressed as 8-h time-weighted average (TWA) concentrations. It was assumed that the RCS exposure for the remainder of the work shift was zero for the following reasons: the worker was carrying out non-stonework activities such as driving a forklift or transporting finished stone pieces to the monument, and the worker being monitored was working away from the stone workshop or any colleagues carrying out stonework. The exposure data were approximately log normally distributed and the geometric mean (GM) and geometric standard deviation of the 8-h TWA average exposure data were calculated.

For testing compliance with the Occupational Exposure limit value (OELV) the joint document by the British and Dutch occupational hygiene societies (BOHS and NVvA) on ‘Testing Compliance with Occupational Exposure Limits (OELs) for Airborne Substances’ (BOHS, 2011) was followed. Exposure data were categorized into similar exposure groups based on material and task and compliance was estimated by comparing the 95th percentile of the exposure distribution with the OELV (BOHS, 2011).

In order to investigate determinants of RCS exposure and their contribution to the individual’s mean exposure, mixed-effects modelling with forward inclusion of the variables was carried out using the log-transformed RCS 8-h TWA data for materials granite and sandstone \((n = 65)\) as the dependant variable. RCS 8-h TWA data for materials limestone and lime mortar were not included in the model because of the large number of non-detect data. Material worked on, worker task, RPE, LEV, job title, weather, level of enclosure, and task duration were introduced as fixed variables, and three sources of random variance were looked at—between-depot variability, between-workers...
within-depot variability, and within-worker variability. RPE and LEV each had two levels depending on whether they were present or not. Enclosure had three possible levels (indoors, outdoors, and partial enclosure), while weather was grouped into six levels (wet and windy, dry and windy, wet and still, dry and still, showers and damp, and sunny). Forward stepwise regression was used to introduce variables significant at the $P \leq 0.001$ level one at a time. Variables were added until no improvement to the model was made. The results of the regression modelling were reported as $\beta$, SE and $\text{Exp}(\beta)$. $\beta$ is the coefficient of the fitted line from the regression modelling, and SE is the standard error of the estimated $\beta$. As the regression modelling was carried out with data on the log scale, the back transformation of the $\beta$ ($\text{Exp}(\beta)$) was also determined. In this context, the $\text{Exp}(\beta)$ could be described as the ratio of the GMs and can be interpreted as the percentage increase (or decrease) in exposure associated with the factor (compared with the baseline factor level).

The extent of reduction in the between-depot, between-worker (within-depot), and within-worker variance components was also investigated. For results below the LOD, levels were imputed following a technique described by Lubin et al., (2004). This involved replacing below LOD values with randomly imputed values between zero and the LOD. A single imputation was carried out. All statistical analyses were performed using GenStat software (14th Edition; VSN International Ltd).

**RESULTS**

**Exposure controls walk-through survey**

All depots contained one stone cutting workshop which contained the following tools: a water-cooled primary cutting saw and hand tools including disc polisher/cylinder polisher; 5″, 9″, and 12″ angle grinders; pneumatic chisels; hand chisels; brushing tools; and hand punches, as well as a centralized LEV system. The LEV system included one or more movable extraction arms (Nederman Extraction Arm Original) (Nederman, 2010) connected at various locations around the workshop to centralized ducting. The ducting was connected to a Nederman L-PAK 250 compact stationary high-vacuum unit. The inlets used on the extraction arms were plastic with a hood diameter of 16 cm. The filtered air was emitted to the external environment through a vent. The water-cooled primary cutting saw was a bridge saw with a 2 m blade. Water was applied to the blade via a recirculating tank at a rate of 100–120 l min$^{-1}$.

Results of the walk-through survey indicated that there were control measures present in all depots, but they were regularly misused or inadequate for the task. Recommended guidance on engineering controls for stone masonry work involving power tools (HSE, 2006) were not complied with on any of the sites visited. A centralized LEV system was present in all depots, and although there was evidence of correct installation, this system was purchased without consultation with the workers or consideration of the work processes to be controlled. Issues regarding the use of the LEV system observed in all depots included the worker not working within the capture zone of the LEV and the capture arm being unable to deal with the high volumes of dust from tasks such as cutting and grinding.

The LEV systems in place, although working as per specification (capture velocity 11 m s$^{-1}$, $n = 12$), were not suitable for the processes that were being carried out in the workshop. The tasks of grinding and cutting stone with a 5″, 9″, and 12″ grinder produced large clouds of dust-laden air too rapidly for it to be captured by the capture arm. Workers regularly worked with large pieces of stone up to 3 m in length, and it was not practical for the worker to regularly reposition the arm as this involved him stopping the task periodically. Capture arms are not recommended for these work tasks for this reason (HSE, 2001, 2011).

RPE was provided in all depots; however, the RPE used by workers varied widely and included nuisance dust masks, positive air purifying respirators, and disposable or reusable negative pressure RPE which in the majority of cases was an FFP3-disposable respirator or half-mask respirator with combination filters. Most RPE had an assigned protection factor of 20. However, there was no evidence of a workplace RPE program comprising of training, fit testing, and a formal purchasing policy for RPE.

**Exposure measurements**

A total of 103 exposure measurements were collected from 35 stoneworkers. Sampling times ranged from 30–375 min with a median sampling time of 240 min. Repeated measurements were obtained for 19 workers, with the number of repeated measurements for each worker ranging from 2 to 16. Worker tasks measured
included cutting stone on a water-cooled primary saw, cutting stone with 5”, 9”, and 12” angle grinders, grinding stone with 5” angle grinders, decorating stone with hand and pneumatic chisels, and repointing with a trowel. Stone materials worked on included sandstone, limestone, granite, and lime mortar. RPE was used by workers in 52% of the work tasks sampled. LEV capture hood systems installed were used for all grinding, cutting, and decoration tasks carried out in the stone workshops. Water suppression was used as the primary exposure control on the primary saw.

Figure 1 provides an example of results obtained with the SidePak photometer, which clearly shows the influence of three different tasks carried out by three different workers (grinding sandstone with a 5” angle grinder in a partially enclosed workshop, cutting sandstone with a 5” grinder in an enclosed work space, and repointing with lime mortar outdoors) on the dust exposure. During the grinding task, peaks in the dust measurements were due to the worker working outside of the capture zone of the LEV. During the cutting task, between the periods 11.13 and 11.53, the worker was not actively involved in stonework.

Table 2 presents a summary of the personal RCS exposure levels (mg m\(^{-3}\); 8-h TWA) grouped by material worked on and task. All active stonework and related activities carried out during the work shift were sampled and therefore 8-h TWA exposure levels presented are representative of full-shift exposures. RCS exposure for workers working with limestone and repointing with lime mortar (n = 38) ranged from <0.02 to 0.06 mg m\(^{-3}\) (8-h TWA). RCS exposure for tasks involving granite ranged from 0.02 to 0.21 mg m\(^{-3}\); 30% of these measurements exceeded the Irish OELV of 0.1 mg m\(^{-3}\). RCS exposure levels for tasks involving sandstone ranged from <0.02 to 6.00 mg m\(^{-3}\) (8-h TWA); 57% of these measurements exceeding the Irish OELV of 0.1 mg m\(^{-3}\). Highest RCS exposure values were recorded for the task of grinding (using a 5” angle grinder; GM = 0.70 mg m\(^{-3}\)) and cutting (using 5”, 9”, and 12” angle grinders) sandstone (GM = 0.70 mg m\(^{-3}\)), respectively (Table 2). Lowest RCS exposure values were recorded for the task of repointing with lime mortar (GM = 0.005 mg m\(^{-3}\)). Table 3 presents the

1 Photometer results for grinding sandstone with 5” angle grinder in partial enclosure, cutting sandstone with 5” angle grinder indoors and repointing with lime mortar outdoors.
Determinants of RCS exposure

The percentage of measurements that exceeded the Irish OELV (0.1 mg m\(^{-3}\); HSA, 2011), the occupational exposure standard recommended by the Scientific Committee on Occupational Exposure Limit Values (SCOEL) values (0.05 mg m\(^{-3}\); SCOEL, 2002) and the threshold limit value (TLV) recommended by

Table 2. Worker personal RCS exposure concentration data (mg m\(^{-3}\); 8-h TWA) grouped by material and worker task

<table>
<thead>
<tr>
<th>Material and task</th>
<th>nm</th>
<th>nw</th>
<th>RCS, mg m(^{-3})</th>
<th>GM(^a) Geometric standard deviation</th>
<th>Range 8-h TWA, mg m(^{-3})</th>
<th>Values &lt; LOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GM(^a)</td>
<td>Range 8-h TWA, mg m(^{-3})</td>
<td>Values &lt; LOD</td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting angle grinder(^c)</td>
<td>10</td>
<td>8</td>
<td>0.70</td>
<td>2.2</td>
<td>0.26–1.30</td>
<td>0</td>
</tr>
<tr>
<td>Cutting water-cooled primary saw</td>
<td>16</td>
<td>6</td>
<td>0.02</td>
<td>3.9</td>
<td>&lt;0.02–0.13</td>
<td>6</td>
</tr>
<tr>
<td>Grinding angle grinder(^d)</td>
<td>22</td>
<td>4</td>
<td>0.70</td>
<td>4.5</td>
<td>&lt;0.02–6.00</td>
<td>0</td>
</tr>
<tr>
<td>Decoration hand and pneumatic chisel</td>
<td>7</td>
<td>6</td>
<td>0.008</td>
<td>9.0</td>
<td>&lt;0.02–0.07</td>
<td>5</td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting angle grinder(^c)</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
<td></td>
<td>&lt;0.02</td>
<td>1</td>
</tr>
<tr>
<td>Grinding angle grinder(^d)</td>
<td>7</td>
<td>3</td>
<td>0.008</td>
<td>1.7</td>
<td>&lt;0.02</td>
<td>7</td>
</tr>
<tr>
<td>Decoration hand and pneumatic chisel</td>
<td>7</td>
<td>4</td>
<td>0.007</td>
<td>4.2</td>
<td>&lt;0.02–0.03</td>
<td>5</td>
</tr>
<tr>
<td>Lime mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repointing</td>
<td>23</td>
<td>17</td>
<td>0.005</td>
<td>2.7</td>
<td>&lt;0.02–0.06</td>
<td>22</td>
</tr>
<tr>
<td>Granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting water-cooled primary saw</td>
<td>4</td>
<td>2</td>
<td>0.01</td>
<td>4.3</td>
<td>&lt;0.02–0.21</td>
<td>2</td>
</tr>
<tr>
<td>Grinding angle grinder(^d)</td>
<td>6</td>
<td>3</td>
<td>0.06</td>
<td>2.7</td>
<td>&lt;0.02–0.21</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^a\)Samples below the analytical LOD for cristalline silica are reported as <0.02mg.
\(^b\)GM values are computed from the data including the imputed data for the values below LOD.
\(^c\)Grinding carried out with 5” angle grinder.
\(^d\)Cutting carried out with 5”, 9” and 12” angle grinder.

Table 3. Worker personal RCS exposure concentration data (mg m\(^{-3}\); 8-h TWA) grouped by material compared to Irish OELV, SCOEL recommended OELV, and ACGIH TLV for RCS

<table>
<thead>
<tr>
<th>Material</th>
<th>% &gt;0.1(^a) mg m(^{-3})</th>
<th>% &gt;0.05(^b) mg m(^{-3})</th>
<th>% &gt;0.025(^c) mg m(^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>57</td>
<td>67</td>
<td>76</td>
</tr>
<tr>
<td>Limestone</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Lime mortar</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Granite</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

\(^a\)0.1 mg m\(^{-3}\) is the Irish OELV.
\(^b\)0.05 mg m\(^{-3}\) is the SCOEL recommended OELV.
\(^c\)0.025 mg m\(^{-3}\) is the ACGIH TLV.
the American Conference of Governmental Industrial Hygienists (ACGIH; 0.025 mg m$^{-3}$; ACGIH, 2008).

For tasks involving sandstone, 67 and 76% of RCS exposure levels exceeded the SCOEL recommended OELV of 0.05 mg m$^{-3}$ and the ACGIH TLV of 0.025 mg m$^{-3}$, respectively. Fifty percent of tasks involving granite exceeded the ACGIH TLV of 0.025 mg m$^{-3}$, and 7 and 4% of measurements involving limestone and lime mortar, respectively, exceeded 0.025 mg m$^{-3}$ (Table 3 and Fig. 2).

Table 4 shows the coefficients of the fixed effects in the optimal model presented as $\beta$, SE, and Exp($\beta$). Due to the natural nesting of workers within depots, three sources of random variance were looked at—between-depot variability, between-workers within-depot, and within-worker variability using mixed effects models (Table 5). After inclusion of the random terms of depot and worker in the model, the fixed effect that was found to be significantly associated with RCS exposure and therefore included in the model was task. Material (granite or sandstone), enclosure, RPE, weather, LEV, and task duration were not found to improve the model so were not included. Table 4 illustrates that the tasks of grinding and cutting result in average RCS exposures of between 32 and 70 times the exposures recorded for the task of decorating. No estimate was calculated for the task of repointing as this task was not carried out with sandstone or granite. The between-depot, between-worker, and within-worker variance components were reduced by 46, 89 and 49%, respectively, after including task in the mixed effects model (Table 5). The between-worker within-depot variance component was reduced from 0.80 to 0.09, after including task in the model, suggesting that the differences in exposure between workers (within a depot) was predominantly due to differences in tasks between the workers.

**Discussion**

**Exposure concentrations**

RCS exposure data for stoneworkers involved in the restoration of historic properties are presented in this article. While exposure to RCS has been well

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2 Worker personal RCS exposure concentration data (mg m$^{-3}$; 8-h TWA) grouped by material compared with Irish OELV, SCOEL recommended OELV, and ACGIH TLV for RCS.
Determinants of RCS exposure documented in the mining and construction sectors amongst others, there are limited exposure data for stoneworkers involved in restoration stonework and also for stoneworker tasks involving high silica content materials such as sandstone. Exposure concentrations (<0.02–6 mg m\(^{-3}\) RCS 8-h TWA) are within the range of those reported in the literature by HSE (2009; <0.02–7.85 mg m\(^{-3}\) 8-h TWA). Highest concentrations were reported for grinding and cutting of sandstone with 5", 9", and 12" angle grinders, and lowest concentrations were found for repointing with lime mortar and work with limestone. The RCS exposures found in this study are higher than those reported for stone workers involved in other sectors, such as construction/roofing (0.04–1.21 mg m\(^{-3}\) RCS 8-h TWA), construction/tuck pointing (0.59–2.84 mg m\(^{-3}\) 8-h TWA), construction/concrete milling and drilling (0.03–1.3 mg m\(^{-3}\) RCS 8-h TWA), demolition workers (0.03–1.3 mg m\(^{-3}\) RCS 8-h TWA), and granite top fabrication (0.04–0.77 mg m\(^{-3}\) RCS 8-h TWA). The higher concentrations reported in this study are most likely as a result of the high quartz content of the materials used by the workers, i.e. sandstone (33–82% quartz content) and the large aerosol concentrations created during the tasks involving grinding tools with inadequate engineering controls. It was established that exposure control practices were inadequate for the exposures concentrations found in this study. There was a high reliance on RPE to control exposure; however, the RPE used was not always appropriate, was poorly maintained, and was not face-fit tested. The LEV that was present was not fit for purpose, was often used incorrectly, and was unsuitable for tasks such as grinding and cutting with angle grinders. It was concluded that the current exposure controls in place would not be adequate to reduce exposures to acceptable levels. This was confirmed by the statistical analyses of the data, which showed that the LEV systems currently used in the depots did not reduce

### Table 4. Coefficients for variables affecting exposure to RCS dust in final mixed effects model of the log-transformed exposure to RCS dust among restoration stoneworkers

<table>
<thead>
<tr>
<th>Model 1 (null model)</th>
<th>Model 2 (model 1 + task)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>SE</td>
</tr>
<tr>
<td>Intercept</td>
<td>-1.990</td>
</tr>
<tr>
<td>Task</td>
<td></td>
</tr>
<tr>
<td>Decorating</td>
<td>0</td>
</tr>
<tr>
<td>Wet cutting</td>
<td>0.67</td>
</tr>
<tr>
<td>Grinding</td>
<td>3.48</td>
</tr>
<tr>
<td>Dry cutting</td>
<td>4.25</td>
</tr>
</tbody>
</table>

^a\( \text{Exp}(\beta) \) is the GM ratio and can be interpreted as the percentage increase in exposure associated with the task (compared with the baseline decorating). ^bThe baseline is decorating.

### Table 5. Estimated variance components for the random effects and mixed-effects models of the log-transformed exposure to RCS dust among restoration stoneworkers, where below LOD values substituted with imputed values

<table>
<thead>
<tr>
<th>Between-depot variance component</th>
<th>Between-worker within-depot variance component</th>
<th>Within-worker variance component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1 (null model)</td>
<td>1.30</td>
<td>0.80</td>
</tr>
<tr>
<td>Model 2 (model 1 + task)</td>
<td>0.70</td>
<td>0.09</td>
</tr>
</tbody>
</table>
exposure significantly. In Ireland, the OELV for RCS is 0.1 mg m\(^{-3}\) 8-h TWA (HSA, 2011); a total of 57% of the measurements involving sandstone in this study were well in excess of this value, and 67% were in excess of the OELV recommended by SCOEL of 0.05 mg m\(^{-3}\). Exposure to RCS is associated with a wide range of ill health effects, and the RCS levels reported in this study indicate that members of this occupational group are likely to be at significant risk of overexposure whilst carrying out certain tasks. Although SCOEL recommends an OELV of 0.05 mg m\(^{-3}\), the occupational exposure limit for RCS in Ireland and the UK is 0.1 mg m\(^{-3}\). There is pressure on regulatory agencies to adopt a lower occupational exposure standard; however, progress on this issue has been hindered by issues related to the reliability of the analytical method at lower RCS concentrations (Stacey, 2007). SCOEL has recommended that, to eliminate silicosis, the OELV for RCS should be below 0.05 mg m\(^{-3}\); therefore, the exposure concentrations found in this study have the potential to cause serious health problems among the workers exposed. It is envisaged that the OELV recommended by SCOEL of 0.05 mg m\(^{-3}\) will be included in the European Carcinogens Directive or as a binding OELV in the European Chemical Agents Directive once the analytical challenges associated with measuring these low levels of RCS are addressed (Cherrie et al., 2011). The reduction of the OELV and the strict obligations associated with handling a substance listed in the Carcinogens Directive puts greater emphasis on investigating suitable controls for tasks that consistently generate RCS concentrations at levels above the OELV.

**Determinants of exposure**

Exposure data were used to investigate determinants of RCS exposures in order to identify high-risk tasks for a future workplace intervention study. In the mixed-effects model, task was found to be the only significant \((P < 0.001)\) determinant of RCS exposure. Task explained most of the between-worker variance within a depot. This can be explained by the fact that within a depot, certain individuals are responsible for specific tasks as they are trained on the equipment required to carry out the task. Task also reduced the day-to-day and between-depot variance by 49 and 46%, respectively. The reduction in the between-depot variance could be explained by the specialized nature of the work performed at certain depots during the study, for example; due to the availability of a stone cutter, one depot specialized in stone cutting work and another depot focused on repointing a nearby monument. After taking into account the differences in exposure between tasks, the day-to-day or within-worker variance was the largest component followed by the between-depot variance component and the between-worker variance component. Intermittent processes, outdoor work, and mobile work have been described as being associated with increased within-worker variability (Kromhout et al., 1993). The remaining within-worker variance could be related to the fact that the majority of stoneworkers in this study are both mobile and working outdoors whilst located on site. Much of the stonework evaluated in this study would also be intermittent, with periods when the worker would be measuring, marking out, and moving the piece of stone in between active stonework.

**CONCLUSION**

Findings from this study indicate that restoration stoneworkers grinding and cutting sandstone are regularly overexposed to RCS dust, compared with the Irish OELV of 0.1 mg m\(^{-3}\) and SCOEL recommended OELV of 0.05 mg m\(^{-3}\) with much lower exposures reported for decorating and wet cutting. Workplace controls, LEV, and RPE provided were not adequate for high-exposure tasks carried out by these workers.

Results from the mixed-effects regression analysis indicates that task is a strong predictor of RCS exposure with the tasks of cutting and grinding sandstone associated with very high levels of RCS exposure. Results also show within-worker variance to be larger than the between-depot variance and between-worker within-depot variance. Hence, any technical interventions should be focused predominantly on grinding and dry cutting tasks and should be appropriate for both workshop and field-based tasks.

**FUNDING**

Commissioners of Public Works in Ireland.

**ACKNOWLEDGEMENTS**

This research work was supported by a research grant from the Commissioners of Public Works in Ireland. The authors would like to thank all the stoneworkers who participated in this study and the depot managers...
and foremen for their cooperation. We would also like to thank the Institute of Occupational Medicine, Edinburgh for laboratory analysis of RCS samples.

REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH). (2008) TLVs and BEIs based on the documentation of the threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: ACGIH.

Archer JD, Cooper GS, Reist PC et al. (2002) Exposure to respirable crystalline silica in eastern North Carolina farm workers. AIHA J (Fairfax, Va); 63: 750–5.


Fayerweather WE, Trumbore DC, Johnson KA et al. (2011) Quantitative exposure matrix for asphalt fume, total particulate matter, and respirable crystalline silica among roofing and asphalt manufacturing workers. Inhal Toxicol; 23: 668–79.


Health and Safety Executive. (2011) Controlling airborne contaminants at work, a guide to local exhaust ventilation (LEV).


