Ann. Occup. Hyg., 2014, Vol. 58, No. 9, 1155–1167
doi:10.1093/annhyg/meu069
Advance Access publication 26 September 2014

The Chartered Society for Worker Health Protection

An Evaluation of On-Tool Shrouds for Controlling Respirable Crystalline Silica in Restoration Stone Work

Catherine B. Healy[1], Marie A. Coggins[1*], Martie Van Tongeren[2], Laura MacCalman[2] and Padraic McGowan[3]

1.School of Physics, National University of Ireland, Galway, Ireland
2.Institute of Occupational Medicine, Research Avenue North, Riccarton, Edinburgh EH14 4AP, UK
3.Irish Commissioners for Public Works, Jonathan Swift Street, Trim, Co Meath, Ireland
*Author to whom correspondence should be addressed. Tel: +353-91-495056; fax: +353-(0)91-494584; e-mail: marie.coggins@nuigalway.ie
Submitted 14 April 2014; revised 27 July 2014; revised version accepted 28 July 2014.

ABSTRACT

Objectives: The task of grinding sandstone with a 5-inch angle grinder is a major source of exposure to respirable crystalline silica (RCS), known to cause diseases such as silicosis and lung cancer among workers who work with these materials. A shroud may be a suitable engineering control for this task. The objectives of this study were to evaluate the effectiveness of four commercially available shrouds at reducing respirable dust and RCS levels during the task of grinding sandstone using tools and accessories typical of restoration stone work.

Methods: The task of grinding sandstone with a 5-inch angle grinder, equipped with different grinding wheels, was carried out over three trials at a restoration stone masonry site. Photometric and RCS data were collected when a 5-inch grinder, equipped with different grinding wheels, was used to grind sandstone with and without a shroud. A total of 24 short duration samples were collected for each no shroud and with shroud combination. Worker feedback on the practicalities of each shroud evaluated was also collected.

Results: Respirable dust concentrations and RCS were both significantly lower ($P < 0.001$) when the grinders were equipped with a shroud compared with grinders without a shroud. Total geometric mean (GM) photometric respirable dust levels measured when grinding with a shroud were 0.5 mg m^{-3}, a reduction of 92% compared to grinding without a shroud (7.1 mg m^{-3}). The overall GM RCS concentrations were reduced by the use of a shroud by 99%. GM photometric exposure levels were highest when using the Hilti 5-inch diamond grinding cup and Diamond turbo cup and lowest when using the Corundum grinding point.

Conclusions: Concentrations of respirable dust and RCS can be significantly reduced by using commercially available shrouds while grinding sandstone with a 5-inch angle grinder in restoration stonework. The short-term photometric respirable dust and RCS measurements collected with and without a shroud indicate that dust and RCS concentrations are reduced by between 90 and 99%. Supplemental exposure controls such as respiratory protective equipment would be required to reduce worker 8-h time-weighted average RCS exposure to below the Scientific Committee on Occupational Exposure Limits recommended occupational exposure limit value of 0.05 mg m^{-3} and the American Conference of Governmental Industrial Hygienists threshold limit value of 0.025 mg m^{-3}.

KEYWORDS: local exhaust ventilation; respirable dust; silica exposure

INTRODUCTION

Inhalation of respirable crystalline silica (RCS) is linked to chronic lung diseases such as silicosis (Landrigan *et al.*, 1986; Rosenman *et al.*, 1996; Forastiere *et al.*, 2002; Leung *et al.*, 2012), lung cancer (Siemiatycki *et al.*, 1989; International Agency for Research on Cancer, 1997), and chronic obstructive pulmonary disease (Oxman *et al.*, 1993). Despite decades of prevention efforts, workers are still regularly exposed to RCS in the work place (Flanagan *et al.*, 2006; Garcia *et al.*, 2006; Healy *et al.*, 2014). It is estimated that ~5.3 million workers in Europe (Cherrie *et al.*, 2011) and ~1.7 million workers in the USA (Occupational Safety and Health Administration, 2004) are exposed to RCS. There is increasing pressure on regulatory bodies to reduce the occupational exposure limit for RCS to <0.05 mg m^{-3} in order to eliminate silicosis [Scientific Committee on Occupational Exposure Limits (SCOEL), 2002], and the development and use of controls to prevent and control RCS exposures to lower levels continues to be a priority.

Grinding stone with hand-held power tools within the construction, restoration, and monumental stone trades has been associated with high RCS exposures, frequently in excess of 0.05 mg m^{-3} [Simcox *et al.*, 1999; Flanagan *et al.*, 2006; Health and Safety Executive (HSE), 2009; Phillips *et al.*, 2013; Healy *et al.*, 2014]. A number of studies have investigated the effectiveness of on-tool shrouds for controlling concrete dust during concrete grinding in the construction sector (Akbar-Khanzadeh and Brillhart, 2002; Echt and Sieber, 2002; Flanagan *et al.*, 2003; Croteau *et al.*, 2004; Akbar-Khanzadeh *et al.*, 2007; 2010). Results from these studies indicate that the use of shrouds can substantially reduce respirable dust (by up to 99%) and RCS concentrations, although not always <0.05 mg m^{-3} 8-h time-weighted average (TWA) (SCOEL) or 0.025 mg m^{-3} 8-h TWA [American Conference of Governmental Industrial Hygienists (ACGIH)]. Few recent studies have investigated respirable dust and RCS levels associated with shrouds outside of the construction sector (HSE, 2001), when working with a material other than concrete (Tjoe Nij *et al.*, 2003). Restoration stoneworkers can be distinguished from other stone work groups, such as those in construction, by their regular use of different grinding tools and grinding wheels unique to the trade. Decorative stone work carried out by a restoration stoneworker is often more detailed and precise than that of a construction stone mason, requiring the worker to position themselves close to the work and dust source (English Heritage, 2012; Healy *et al.*, 2014). For this reason, exposure controls marketed towards, and suitable for stone masonry in other sectors, may not always be suitable for restoration stone work. In addition, restoration stoneworkers are often required to adhere to conservational guidelines and to work with traditional materials and techniques. Hence, the elimination or substitution of high silica content materials, for example sandstone or granite, is usually not an option. Sandstone is a naturally occurring material, regularly used by restoration stone masons, with a silica content of between 52 and 90%. Sandstone not only has a framework consisting of predominantly silica grains but is also often bound together by a silica rich cementing agent (Pettijohn *et al.*, 1987; McBride, 1985).

Previous studies have shown that there is a high reliance on respiratory protective equipment (RPE) in stone masonry (HSE, 2009; Healy *et al.*, 2013; 2014). Hence, studies investigating the effectiveness of engineering controls for this sector are important. Water suppression can be an effective control for grinding (Akbar-Khanzadeh *et al.*, 2010) however, limitations in workshop design and the large proportion of tasks carried out on location means this control is often not an option. Shrouds are potentially the most practical method for controlling exposure to RCS during restoration work. However, the nature of the work, as well as the composition of the sandstone, compared with cement, could potentially influence the effectiveness of shrouds to reduce worker exposure to RCS and respirable dust.

This paper reports on the final component of a larger study on determinants of RCS exposure in restoration stone masonry (Healy *et al.*, 2014). Previously, we identified the task of grinding sandstone with a 5-inch angle grinder as creating high exposure to RCS among restoration stoneworkers (Healy *et al.*, 2014). The objective of this current study was to examine the effectiveness of four commercially available shrouds at reducing RCS levels when used by restoration stoneworkers to grind sandstone using tools and techniques typical of their occupation.

MATERIALS AND METHODS

Site location and description

This study was repeated on three occasions at a stone workshop in the Republic of Ireland. The site had access to sufficient quantities of sandstone, stationary and mobile vacuum units, 5-inch grinders, and grinding wheels needed in order to carry out the trial. The measurements were conducted in the semi-enclosed workspace adjacent to the stone workshop. The workspace had a corrugated metal roof and was enclosed on three sides by a plastic mesh and was open to the front. The workspace comprised of a bench and a rotating banker which is a type of stonemasonry bench and had facility for on-tool local exhaust ventilation (LEV) systems connected to a Nederman (Nederman Sverige AB, Helsingborg, Sweden) L-PAK 250 compact stationary high-vacuum unit in the workshop. Two experienced restoration stoneworkers were recruited for the evaluation of all exposure controls in this study. One stoneworker participated in trials 1 and 2 and the second stoneworker participated in trial 3. During this study, workers wore a powered air purifying respirator or an FFP3 dust mask both with an assigned protection factor of 20.

Tasks evaluated

During the first trial, sandstone was shaped to fabricate and assemble a sandstone fireplace for a castle, while during the second and third trial, a sandstone window jamb, the main vertical parts forming the sides of a window frame, for a castle was constructed. These tasks required the worker to use various abrasive grinding wheels, reflecting typical work and exposure patterns within this occupational group. All work was performed on a rotating banker.

Tools and shrouds evaluated

Eight commercially available shrouds were sourced via consultation with vendors. The workers were asked to assess the practicality of the eight shroud options. Shrouds that had a skirting were rejected as well as shrouds that could not be modified to expose the tip of the grinding wheel. The FLEX shroud was selected for the trial as FLEX grinders were commonplace in the organisation's stone workshops so, it would suit many of the grinders used by these stoneworkers. The Dustie® and Dust Muzzle shrouds were selected as both were universal fit shrouds and the Hilti system was selected as the workers favoured its design features.

Two hand-held electric powered grinders were used in this study; a FLEX (FLEX-Elektrowerkzeuge GmbH, Steinheim, Germany) grinder and a Hilti (Hilti Corporation, Schaan, Liechtenstein) grinder (Fig. 1). Over the course of the trials, the FLEX grinder was equipped with five different grinding wheels commonly used in restoration stone work. These grinding wheels and their specified RPM are detailed below:

- Diamond Teck (Diamond Teck Unit 4, Rathcoole, Dublin, Ireland) Diamond turbo cup grinder, 10 cm operating at 4000 rpm
- Diamond Teck 12.2 cm Multi-cutter diamond cup wheel operating at 4500 rpm
- FLEX 10 cm Velcro diamond disc grade 50 (coarse) operating at 2000 rpm
- Bavaria (Einhell Germany AG, Landau an der Isar, Germany) 10 cm Corundum grinding ring grit 30 with adapter plate operating at 4000 rpm
- Bavaria Corundum grinding point operating at 3000 rpm

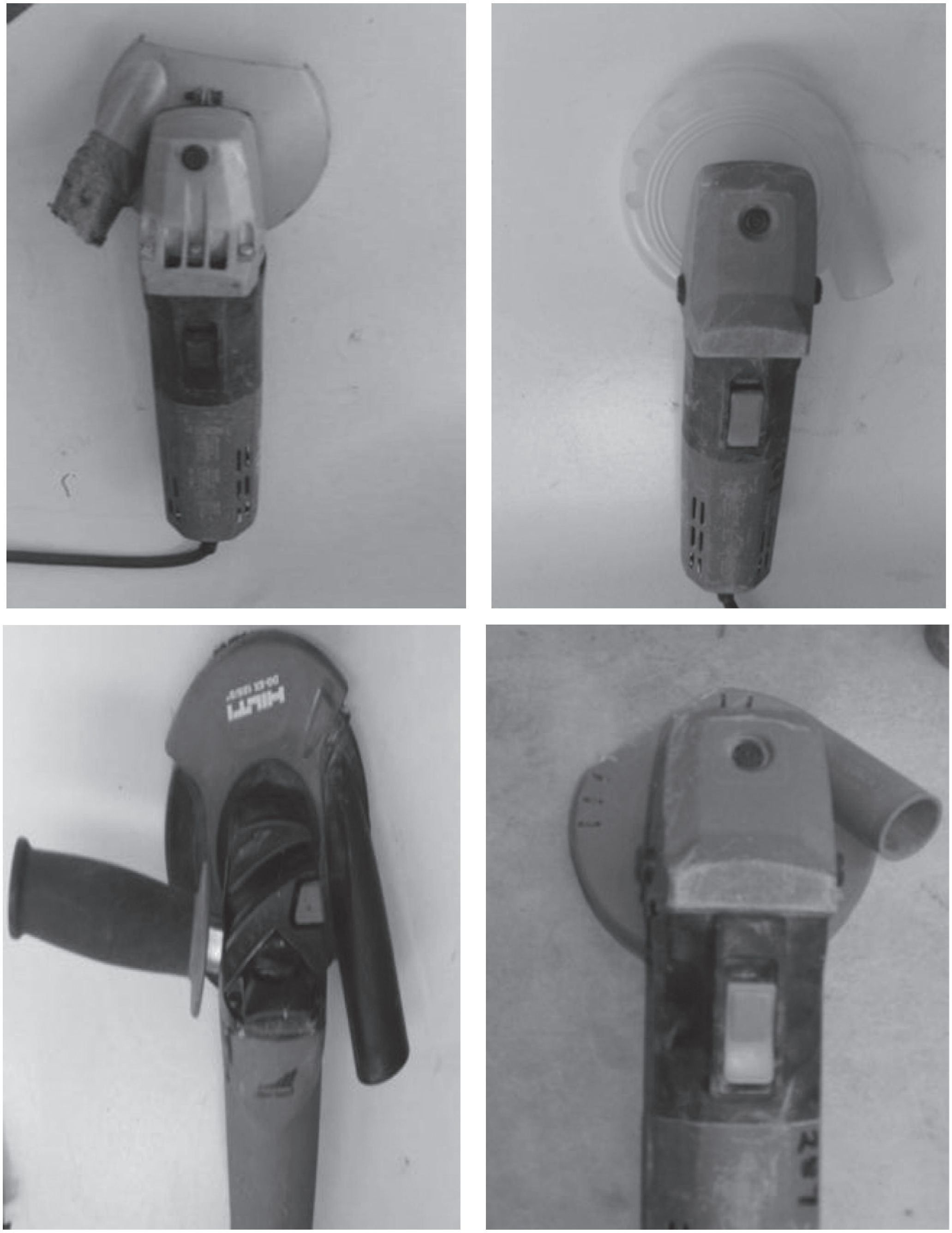
Certain grindings wheels (Diamond turbo cup grinder, Multi-cutter diamond cup wheel) were used to remove excess stone from a sawn block of stone and other grinding wheels (Corundum grinding point, Velcro diamond disc grade 50) were used to create a smooth finish on the flat, in corners and around decorative details (Fig. 2).

Configuration 1

FLEX grinder equipped with a shroud manufactured by FLEX. This shroud was made of steel and had a diameter of 13.5 cm. The exhaust port was 2.7 cm in diameter and was positioned on the right side of the grinder.

Configuration 2

FLEX grinder with Dust Muzzle shroud (PWM Sales Limited, East Yorkshire, UK). This shroud was made of polypropylene and had a diameter of 15 cm. Air entered the shroud through seven vacuum relief holes (diameter 9 mm) positioned on the front exterior. The side exhaust port was positioned on the right side of the grinder and had a diameter of 3 cm. The shroud had an adjustable collar and attached to the bearing housing of the grinder



1 Grinders and shrouds evaluated during trial.

using an adjustable collar ring. The combination of the adjustable collar and collar ring was designed to accommodate different bearing housing diameters. In order for this shroud to be fitted onto the FLEX grinder, 1.8 cm had to be trimmed off the collar by the worker to adjust the height. Also, an 8- × 2.5-cm section was cut from the skirt of the shroud using a saw in order to expose the leading edge of the blade. This modification was carried out by the worker and was essential in order for the worker to cut into corners on the stone.

2 Grinding wheels evaluated with FLEX grinder during trial.

Configuration 3

FLEX grinder equipped with a Dustie® (Dustless Technologies, UT, USA) shroud which was made from flexible lightweight plastic. This combination was used with the Nederman L-PAK 250 compact stationary high-vacuum unit. The diameter of this shroud was 14.5 cm and, similar to the Dust Muzzle, had 10 rectangular 0.8- × 0.1-cm vacuum relief holes positioned on the front exterior. The attachment collar of this shroud was a FLEX-Flange™ which allowed it to fit to various bearing housings and was fitted to the grinder using an adjustable collar ring. Then, 0.7 mm was trimmed off the flange by the worker to fit it on the bearing housing. The section that was cut from the front was 7.5 × 2.5 cm along the 'TP' line. Two cut lines were moulded into the shroud in order to aid the cutting of it to expose the tip of the grinding wheel. The cut line selected depended on the worker's directional preference when cutting. The side exhaust port was located on the right hand side and had a 2.9 cm diameter.

Configuration 4

Hilti grinder with diamond grinding cup equipped with a shroud system manufactured by Hilti (DG-EX 125 dust extraction hood). This combination was used with the Hilti VC20-U portable jobsite vacuum. This shroud was constructed of high-density plastic and had a diameter of 15.5 cm with a 3.3 cm diameter take-off located to the right. The shroud had nine 0.4-cm vacuum relief holes positioned on the bottom of the exterior. The shroud had a design feature, which enabled the worker to slide the front rim of the shroud to the left in order to cut into corners. This grinder operated at 11 000 rpm, in trial 1, it was concluded that this was too high a revolutions per minute for this type of stone work and for this reason, this on-shroud was not tested in trials 2 and 3.

Vacuum sources

A Nederman L-PAK 250 compact stationary high-vacuum unit with a high-efficiency particle air filter (HEPA) filter was used to provide vacuum for three (FLEX, Dustie®, Dust Muzzle) of the shrouds tested. The unit (dimensions 1.3 × 1.1 m) was located in the workshop and was connected to an exterior wall via a length of corrugated hose. This extended down the exterior wall via a 50-mm-diameter metal hose with a valve on the end. This valve had a micro switch which opened automatically when a connected tool was powered on. The tool was connected to the exterior hose via a flexible 5-m-long, 3.5-cm-diameter corrugated hose. The unit had a two stage filter followed by a HEPA filter (99.97% efficiency at a particle diameter of 0.3 μm). This vacuum unit automatically cleaned its filter by blasting reversed atmospheric air through its surface treated polypropylene filter socks every 60 s, dislodging any dust that may have accumulated into a container located below the unit. For the harmonized Hilti set up, the vacuum used was Hilti's VC20-U portable jobsite vacuum. This vacuum was a dry/wet vacuum cleaner and is marketed for 'removing dust from drilling, slitting, grinding, cutting, and dry coring'. The portable vacuum had the dimensions 0.5 × 0.38 × 0.5 m and a weight of 13.5 kg. The vacuum was equipped with a standard disposable filter. The vacuum was conveyed to the tool via a flexible 5-m-long 3.6-cm-diameter corrugated hose. This vacuum was equipped with an automatic filter cleaning system, which cleaned the filter every 15 s to provide consistently high suction performance.

Experimental design

Evaluation of the effectiveness of the shrouds at reducing airborne respirable dust and RCS concentrations was assessed by collecting photometric (n = 112) and RCS (n = 56) data. There were three trials and measurements were repeated eight times within a trial. Each trial lasted 1 day. For the FLEX grinding tool, one trial resulted in 8 photometric and 4 RCS measurements using the FLEX grinding tool with no shroud and 8 photometric and 4 RCS measurements for each of the 3 shrouds tested, with a total of 32 photometric and

16 RCS measurements for each trial. The Hilti shroud was evaluated in the first trial only where eight photometric and four RCS measurements were taken using the Hilti tool with no shroud and eight photometric and four RCS measurements for the Hilti shroud. The measurement duration was 15 min with and 10 min without a shroud. These sampling durations were selected based on anticipated levels of exposure concentrations during the task evaluated. The measurement duration without a shroud was reduced in order to avoid exposing the worker to high levels of RCS when grinding sandstone. Measurements without a shroud were collected at the end of each trial to reduce background contamination during the shroud measurements. In all three trials, the measurements with and without a shroud were collected in direct succession to maintain consistent parameters like weather conditions. The order in which the shrouds were evaluated varied randomly, ensuring that differences in technique used at the beginning and end of the process would not affect the evaluation of the shrouds.

RCS sampling

Personal respirable dust samples were collected using a Higgins Dewell cyclone (Casella, Bedford, UK) attached to an air sampling pump (Sidekick pump; SKC Ltd, Dorset, UK) calibrated pre- and post-sampling to a flow rate of 2.2 l min^{-1} using a primary air flow meter (DryCal DC Lite; BIOS International, NJ, USA). The sampling medium used was 25 mm, 5-μm pore size PVC filters. The Higgins Dewell cyclone and filter cassette was attached to the worker's lapel. A new filter cassette was placed in the Higgins Dewell cyclone for each test carried out and the cyclone was cleaned with compressed air between each test. A different Higgins Dewell cyclone was used for tests carried out with and without a shroud in order to avoid cross-contamination. The silica content of the respirable dust was quantified by X-ray diffraction (XRD) as per MDHS 101 HSE (2005). In addition to the personal samples, a bulk sample of the sandstone used in the trial was submitted for analysis to quantify the percentage silica content of the sandstone. The percentage silica in the bulk sample was quantified by XRD. All laboratory analytical analyses were carried out by UKAS accredited laboratory, the Institute of Occupational Medicine (IOM) in Edinburgh, UK. Samples below the analytical limit of detection (LOD) for crystalline silica were reported as <0.02 mg and the LOD for bulk sample analysis was 0.3%.

Photometric sampling

Photometric data were collected in the worker breathing zone using a Sidepak AM510 personal aerosol monitor (TSI Incorporated, Shoreview, MN, USA) with a Dorr-Oliver cyclone attachment. Prior to use, the photometer was calibrated to the recommended flow rate of 1.7 l min^{-1} using a primary air flow meter (DryCal DC Lite; BIOS International). The photometer had a measurement range of 0.001–20 mg m^{-3}. A different photometer sampling train was used for tests carried out with and without a shroud to avoid cross-contamination. A calibration factor of 3.7 (Healy *et al.*, 2013) was applied to the photometric data to accurately estimate the photometric mass concentration for sandstone dust. The Dorr-Oliver cyclone and photometer was fixed to the worker's lapel. All tasks carried out by the worker were observed by the researcher. For tests involving the FLEX grinder, information on the type of grinding wheel used was recorded.

Vacuum performance

During the first trial, the air velocity near to the vacuum source entry was estimated to determine any change in velocity during the trial using a digital manometer (ZEPHER, Digital Micromanometer: Solomat Neotronics, CT, USA). A 0.6-m copper pipe with a diameter of 50 mm was inserted between the vacuum source and vacuum hose using couplers to ensure a secure fit. A 6-mm measurement hole was drilled in the pipe at a distance of 0.4 m from the vacuum source. At the beginning, middle and end of each task, the manometer was inserted into the measurement hole and a centreline measurement of the air velocity was taken. A piece of tape was placed on the manometer to ensure the manometer was inserted to the same depth.

Data analysis

Photometric and RCS data were approximately log normally distributed and the geometric mean (GM) and geometric standard deviation of the photometric and RCS data were calculated. Measurements less than the LOD of the analytical method for RCS were substituted with a constant value of half the LOD (0.01 mg m^{-3}) using methods described by Hornung and Reed (1990). Using the log transformed respirable dust and RCS data, a student *t*-test was carried out to investigate if there was a statistically significant difference in respirable dust and RCS concentrations when the grinder was used with a shroud and without a shroud. In order to investigate the impact of using different grinding wheels on respirable dust concentrations, general linear regression was carried out using the log transformed photometric data as the dependant variable and after adjusting for the presence or absence of a shroud, grinding wheel and shroud type as the independent variable. All statistical analyses were performed using GenStat software (14th Edition) (VSN International Ltd).

Feedback from workers on use of shrouds

An important aspect of this study was to involve the end user in the exposure control selection process. The researcher collected feedback from the workers by asking them questions regarding the user-friendliness and practicality of the shrouds evaluated. Workers were asked to provide feedback regarding, the durability of the shroud material, attaching the shroud to the grinder and operating the grinder with the shroud in place. The feedback was collected during the trials and from each worker separately. Worker feedback was taken into account in the overall evaluation of each shroud. None of the workers had used any of the shrouds before.

RESULTS

Effectiveness of shrouds at reducing respirable dust and RCS levels

The task of grinding sandstone was carried out using a 5-inch angle grinder and six different grinding wheels, with and without a shroud. A total of 32 photometric and 16 RCS samples were collected when the grinders were used without a shroud. A total of 72 photometric and 36 RCS samples were taken for the shrouds used with the FLEX grinder over three trials. Only eight photometric and four RCS samples were taken for the Hilti shroud during the first trial. Analysis of the bulk sample of sandstone used in the trial determined the sandstone had a silica content of 50.2%. The concentration of respirable dust was reduced by an order of magnitude when the grinders were equipped with a shroud ($n = 80$) compared with grinders without a shroud ($n = 32$) (Table 1).

Total GM corrected photometric respirable dust levels measured when grinding with a shroud were 0.5 mg m^{-3}, a reduction of 92% compared to grinding without a shroud (7.1 mg m^{-3}). Photometric respirable dust exposure reduction for the four shrouds evaluated ranged from 90 to 93%. The FLEX grinder was used with three (FLEX, Dustie®, Dust Muzzle) of the shrouds tested. The Dustie® and Dust Muzzle shrouds

Table 1. GM (GSD) photometric respirable dust concentrations (mg m^{-3}) measured when grinding with and without a shroud

No shroud with shroud								
Tool	***n***	**GM (GSD)**	**Shroud**	***n***	**GM (GSD)**	**Reduction %**	***P* value comparison, no shroud and shroud**	**95 % CI**
All data	32	7.1 (2.9)	All data	80	0.5 (3.6)	92	<0.001	0.91–0.93
FLEX	24	6.1 (3.2)	FLEX	24	0.6 (3.6)	90	<0.001	0.87–0.92
			Dustie®	24	0.4 (3.1)	92	<0.001	0.90–0.94
			Dust Muzzle Ultra	24	0.4 (4.5)	93	<0.001	0.91–0.95
Hilti	8	10.4 (1.9)	DG-EX 125 Dust extraction hood	8	0.9 (2.3)	91	<0.001	0.88–0.93

CI, confidence interval; GSD, geometric standard deviation.

demonstrated the highest reduction in GM respirable dust concentrations with exposure levels reduced from 6.1 to 0.4 mg m^{-3} (92 and 93%, respectively). A significantly lower ($P < 0.001$) exposure reduction of 90% (6.1 to 0.6 mg m^{-3}) was achieved for the FLEX shroud. A significant reduction ($P < 0.001$) of 91% was also achieved by the Hilti shroud from 10.4 to 0.9 mg m^{-3} (Table 1).

RCS concentrations were measured (mg m^{-3}) when grinding with and without a shroud. One sample was below the LOD for silica (0.02 mg m^{-3}) where no shroud was used. For measurements where a shroud was used, 75% (n = 30) were below LOD. The RCS concentrations measured were two orders of magnitude lower when the FLEX and Hilti grinders were equipped with a shroud (n = 36) compared with grinders without a shroud (n = 12) (Table 2). The exposure reductions for the RCS concentrations for the four shrouds were slightly higher to that of the respirable dust exposure reductions (Table 2). Total GM RCS concentrations measured when grinding with a shroud were 0.03, a reduction of 99% compared to grinding without a shroud (4.2 mg m^{-3}). RCS exposure reduction for the four shrouds ranged from 97 to 99%. The Dustie® and Dust Muzzle shrouds demonstrated the highest reduction in GM RCS concentrations with exposure levels reduced by 99% from 3.7 to 0.01 and 0.02 mg m^{-3}, respectively. Due to the high level of non-detects for silica in the RCS data, the confidence intervals in Table 2 are not reliable; however, it is clear that the RCS concentrations are significantly reduced ($P < 0.001$) and the proportion of results below LOD are much higher where a shroud was used compared to where no shroud was used.

When the FLEX grinder was used in this study, it was equipped with five different grinding wheels and the Hilti grinder was equipped with one. Photometric respirable dust levels with no shroud in place were highest when using the Diamond turbo cup grinder (11 mg m^{-3}), Hilti 5-inch diamond grinding cup (10.4 mg m^{-3}), and Multi-cutter diamond cup wheel (10.2 mg m^{-3}) and lowest for the Corundum grinding point (2.5 mg m^{-3}). Similarly, the GM silica concentrations (mg m^{-3}) were highest when using the Diamond turbo cup grinder (1.2 mg) and lowest when using the Corundum grinding point (0.1 mg) when no shroud was in use. The GM photometric exposure levels when a shroud was used were also highest when using the Hilti 5-inch diamond grinding cup (0.9 mg m^{-3}), Diamond turbo cup grinder (0.6 mg m^{-3}), and Multi-cutter diamond cup wheel (0.5 mg m^{-3}) and were lowest when using the Corundum grinding point

Table 2. GM (GSD) RCS concentration (mg m^{-3}) measured when grinding with and without a shroud

No shroud with shroud										
Tool	Values <LOD	n	GM (GSD)	Shroud	Values <LOD	n	GM (GSD)	% Reduction	P value comparison, no shroud and shroud	95 % CI
All data	1	16	4.2 (6)	All data	30	40	0.03 (8)	99	<0.001	0.97–0.99
FLEX	1	12	3.7 (8)	FLEX	7	12	0.07 (12)	98	<0.001	0.86–0.99
				Dustie®	11	12	0.01(3.9)	99	<0.001	0.98- 0.99
				Dust Muzzle Ultra	10	12	0.02 (6)	99	<0.001	0.96–0.99
Hilti	0	4	6 (1.9)	DG-EX 125 Dust extraction hood	2	4	0.1 (21)	97	<0.001	−1.78 to 0.99

CI, confidence interval; GSD, geometric standard deviation.

(0.2 mg m^{-3}). After adjusting for the effect of the shrouds, there was a significant ($P < 0.001$) difference in photometric respirable dust levels depending on the grinding wheel used (Table 3). Table 3 illustrates that the use of a Hilti 5-inch diamond grinding cup and Diamond turbo cup resulted in average photometric respirable dust levels of between 3.5 and 2.6 times the respirable dust levels recorded for the Corundum grinding point. Average respirable dust levels produced by the Corundum grinding ring, Multi-cutter diamond cup, and Velcro diamond disc were 2.3, 2.2, and 1.8 times that of the Corundum grinding point, respectively. Type of shroud was added to the model to investigate if the type of shroud used had an effect on the respirable dust levels produced by the different grinding wheels. After adding grinding wheel to the model and adjusting for the effect of the shrouds, the type of shroud did not improve the model and therefore was not investigated further.

Practical experience

Workers generally indicated that the grinder was easier to use without a shroud especially when working with sandstone. They reported that from their experience, due to its different consistency, limestone dust is emitted from the tool in a more contained cloud and would therefore be more easily captured by a shroud. The primary reason the workers found the grinder easier to use without a shroud was the reduction in visibility when using it however, they did report that cutting the shroud improved this. Transparent shrouds are available to address this problem but are not suitable for work with sandstone. They also reported that the hose attached to the side exhaust port was cumbersome while working but that it would not deter them from using the shroud.

Hilti and FLEX shrouds

Although the Hilti shroud reduced the photometric respirable dust concentrations by 91%, it was concluded that this grinder operated at too high a RPM for restoration stone work. The workers did however find the design feature, which enabled the worker to slide the front rim of the shroud to the left in order to cut into corners very useful.

The FLEX shroud was pre-cut which the workers indicated was beneficial as they could see the cutting

Table 3. GM (GSD) photometric respirable dust concentrations (mg m^{-3}) for grinding wheels when grinding with and without a shroud and coefficients for grinding wheels in regression model of the log transformed photometric respirable dust data

Grinding wheel	No shroud		With shroud		Exp(β)[a]	*P* value
	n	GM (GSD)	*n*	GM (GSD)		
Corundum grinding point[b]	4	2.5 (3.0)	10	0.2 (2.8)	1.0	<0.001
Velcro diamond disc	10	5.7 (3.0)	12	0.4 (2.6)	1.8	<0.001
Multi-cutter diamond cup	2	10.2 (2)	20	0.5 (4.0)	2.2	<0.001
Corundum grinding ring	4	8.6 (1.8)	10	0.5 (2.0)	2.3	<0.001
Diamond turbo cup	4	11 (2.7)	20	0.6 (4.7)	2.6	<0.001
Hilti diamond grinding cup	8	10.4 (2.0)	8	0.9 (2.3)	3.5	<0.001

GSD, geometric standard deviation.
[a]The baseline is Corundum grinding point.
[b]Model adjusted for shroud.

edge on the stone without modifying the shroud. Also, because the FLEX shroud was constructed of metal, the weight of the vacuum hose did not distort the shroud as it did the other shrouds.

Dustie® and Dust Muzzle shrouds

The workers found that by modifying the Dust Muzzle shroud to cut into corners, it was too flimsy which resulted in the grinding wheel penetrating it. This shroud did not have a cutting line moulded onto it which resulted in the worker judging the cut himself which sometimes resulted in interference with the vacuum holes during use. Furthermore, the Dust Muzzle tended to slip up and down the grinder despite the worker's best efforts to secure it. In the worker's opinion, the Dustie® shroud performed better in terms of practicality. The shroud was described as more durable and robust and this shroud fitted more securely onto the bearing housing of the grinder. The Dustie® had two cut lines moulded onto it in order to aid the cutting of it to expose the tip of the grinding wheel, the workers found this facility very beneficial as it also took into account the workers cutting direction preference.

Vacuum performance

During trial 1, the estimated average air velocity measured for the mobile unit was 21 m s^{-1}. There was a small decrease in air velocity during some of the trials. The average air velocity for the stationary vacuum unit was 17 m s^{-1} and also exhibited at times a decrease in transport velocity during trials.

DISCUSSION

Effectiveness of shrouds at reducing respirable dust and RCS levels

The results of this research have demonstrated that respirable dust and RCS concentrations can be significantly reduced by using commercially available shrouds while grinding sandstone with a 5-inch angle grinder in restoration stonework. The short-term respirable dust measurements collected with and without a shroud indicate that dust levels are reduced by between 90 and 93%. Similar to previous studies with shrouds in place (Akbar-Khanzadeh and Brillhart, 2002; Croteau *et al.*, 2002; Flanagan *et al.*, 2003; Croteau *et al.*, 2004; Akbar-Khanzadeh *et al.*, 2007; 2010), we also found concentrations of RCS can still exceed occupational exposure levels [SCOEL occupational exposure limit value (OELV) of 0.05 mg m^{-3}; SCOEL, 2002 and ACGIH threshold limit value (TLV) of 0.025 mg m^{-3}; ACGIH, 2008]. Previous work (Healy *et al.*, 2014) suggests RCS exposure concentrations of <0.02–6.00 mg m^{-3} 8-h TWA are produced for the task grinding sandstone using a 5-inch angle grinder. Therefore, in addition to using a shroud, supplemental exposure controls would be required with an assigned protection factor of at least 5 to reduce 8-h TWA exposures and achieve compliance with the OELV. Reductions in photometric respirable dust concentrations are in agreement with other similar intervention studies (Tjoe Nij *et al.*, 2003; Croteau *et al.*, 2004). Croteau *et al.* evaluated the effectiveness of different shrouds when grinding concrete on six construction sites. This study reported a mean reduction of 92% in photometric respirable dust levels when using grinders equipped with a shroud. Despite the reduction achieved, 22 and 26% of the samples collected while a shroud was used were greater than the SCOEL OELV of 0.05 mg m^{-3}; however, workers would be adequately protected if wearing RPE with an assigned protection factor of 5–10. Tjoe Nij *et al.* evaluated shrouds in the construction sector while workers carried out recess milling, drilling, and cutting of sandstone. This study reported a reduction in photometric respirable dust concentrations of 99% when cutting sandstone with grinders equipped with a shroud.

To the author's knowledge, our study is one of a few (Akbar-Khanzadeh *et al.*, 2010) that has investigated the effectiveness of shrouds at reducing respirable dust and RCS levels while using a 5-inch grinder with different grinding wheels. After adjusting for the effect of the shrouds, there was a significant ($P < 0.001$) difference in the levels of respirable dust measured depending on grinding wheel used and there were no significant differences in the efficiencies between the different types of shrouds with different grinding wheels. The GM of the photometric respirable dust and silica concentration data both when no shroud and shrouds were used were highest for the Hilti 5-inch diamond grinding cup and Diamond turbo cup and were lowest for the Corundum grinding point with average respirable dust levels produced by the Hilti 5-inch diamond grinding cup and

Diamond turbo cup 3.5 and 2.6 times the average respirable dust levels produced by the Corundum grinding point. Lowest levels were reported for the Corundum grinding point and Velcro diamond disc. The Diamond turbo cup and Hilti 5-inch diamond grinding cups are all diamond grinding cups and are generally used to remove excess stone and to carry out rough grinding work whereas abrasive tools like the Corundum grinding point are used to add a very fine finish to the piece such as decorative details and grind into corners. Furthermore, the Hilti 5-inch diamond grinding cup and the Diamond turbo cup operated at 11 000 rpm and 4000–4500 rpm, respectively, compared with the Corundum grinding point (3000 rpm). The shroud may not control the stone dust as effectively from grinding wheels operating at a greater RPM due to the dust being emitted with greater angular momentum and with a larger volume. Akbar-Khanzadeh *et al.* (2010) also reported very high RCS and respirable dust levels when using diamond grinding cups operating at 6000–10 000 rpm as did other studies such as Flanagan *et al.* (2003), who reported a 60% increase in RCS levels when a diamond wheel was employed in comparison to an abrasive wheel. In our study, low levels of RCS and respirable dust were produced when using the Velcro diamond disc grade 50 (an abrasive disc). During the trial, this disc wore out after approximately four tasks, most likely due to the abrasiveness of sandstone which was used in this trial. Based on short-term sample data, the overall mean RCS concentration was reduced by the use of a shroud by 99%, similar to that of previous studies that investigated the effectiveness of shrouds for controlling concrete dust during concrete grinding in the construction sector (Akbar-Khanzadeh and Brillhart, 2002; Flanagan *et al.*, 2003; Croteau *et al.*, 2004) and in simulated lab environments (Akbar-Khanzadeh *et al.*, 2007; 2010). These studies reported a 70–92% (Croteau *et al.*, 2004), 67% (Akbar-Khanzadeh and Brillhart, 2002), and 71% reduction in RCS levels (Flanagan *et al.*, 2003). A reduction in RCS concentrations of 99 and 99.7% were reported by Akbar-Khanzadeh *et al.* (2007; 2010). Despite the exposure reductions achieved by the shrouds in this study, it is important to consider that a lower level of dust control may be achieved by these shrouds when used in an uncontrolled environment. Studies involving concrete grinding, concrete cutting, and masonry tuck pointing have identified factors which influence the effectiveness of shrouds and they include operator technique (Thorpe *et al.*, 1999) the position of the shroud in relation to the surface of the material being worked on (Collingwood and Heitbrink, 2007; Middaugh *et al.*, 2012) and the type of work conducted, e.g. edge work (Croteau *et al.*, 2004).

Finally, as demonstrated in previous work, it is important to consider the workers feedback on the shrouds tested. Worker feedback collected during the course of this study suggested that the Dustie® shroud performed best in terms of practicality. For this reason and based on the exposure reduction achieved, the Dustie® shroud was selected as the most suitable shroud for grinding sandstone with a 5-inch angle grinder for this occupational group.

Evaluation of vacuum performance

A minimum duct/transport velocity of around 20 m s^{-1} is recommended to prevent the settling of dust produced from grinding in the duct (HSE, 2011). The average duct velocity measured was 17–21 m s^{-1}. The mobile vacuum unit had a slightly higher average duct velocity than the stationary vacuum unit. The automatic filter cleaning function was utilized in each trial and both filters were new. The consistency of the sandstone dust and the fact that the pitot tube was facing directly into the air flow, caused regular blockages of the pitot tube which resulted in low velocity measurements recorded on some occasions. The stationary unit was used to provide vacuum for three (FLEX, Dustie®, Dust Muzzle) of the on-tool LEV systems tested, whereas the mobile unit was only used with the Hilti system therefore, directly comparing the differences in dust levels measured between the two vacuums was not possible. Despite the duct velocity of the stationary unit dropping occasionally, it supplied sufficient vacuum to the on-tool LEV to significantly reduce dust levels and reduce 80% of the RCS measurements to < LOD. The mobile vacuum unit also provided sufficient duct velocity to reduce respirable dust levels significantly which is encouraging since many workers, especially those working at field sites, rely on a mobile unit to supply vacuum to LEV and mobile units are also less expensive in comparison to installing a centralized vacuum unit in a workshop. These findings are similar to other studies where despite a drop in velocity, the mobile vacuum still captured dust at acceptable levels and no significant difference in dust levels was observed between tests (Shepherd *et al.*, 2009). Both units were straightforward to use but the mobile vacuum unit requires frequent filter replacement in comparison to the stationary unit, depending on extent of use, which could prove to be a disadvantage. Education of the workers on the importance of changing vacuum unit filters and ensuring management supply the correct filters is important to ensure the ongoing effectiveness of a vacuum unit on site.

CONCLUSION

Findings from this study demonstrate that shrouds are an effective engineering control for reducing respirable dust and RCS concentrations while grinding sandstone during restoration stone work. Four different shrouds reduced respirable dust and RCS concentrations by >97%. Supplemental exposure controls such as RPE would be required in addition to using the shroud to reduce worker 8-h TWA RCS exposure to below the SCOEL-recommended OELV of 0.05 mg m^{-3} and the ACGIH TLV of 0.025 mg m^{-3}. Results also demonstrate the importance of collecting worker feedback on the practicalities of an exposure control. Hence, exposure data should be combined with worker feedback data when selecting an appropriate exposure control for an occupational group.

FUNDING

This research work was completed as part of a research PhD at the National University of Ireland, Galway, and was funded by the Commissioners for Public Works in Ireland.

ACKNOWLEDGEMENTS

The authors would like to thank the stoneworkers who participated in this study and the depot manager for his corporation. We would also like to thank Steve Clarke of the Institute of Occupational Medicine, Edinburgh for his advice and analysis of RCS samples. The authors are also grateful to PWM Distribution, Romsey, UK for providing products for use in this trial.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

REFERENCES

Akbar-Khanzadeh F, Brillhart RL. (2002) Respirable crystalline silica dust exposure during concrete finishing (grinding) using hand-held grinders in the construction industry. *Ann Occup Hyg*; 46: 341–6.

Akbar-Khanzadeh F, Milz S, Ames A *et al.* (2007) Crystalline silica dust and respirable particulate matter during indoor concrete grinding - wet grinding and ventilated grinding compared with uncontrolled conventional grinding. *J Occup Environ Hyg*; 4: 770–9.

Akbar-Khanzadeh F, Milz SA, Wagner CD *et al.* (2010) Effectiveness of dust control methods for crystalline silica and respirable suspended particulate matter exposure during manual concrete surface grinding. *J Occup Environ Hyg*; 7: 700–11.

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.

Cherrie JW, Gorman Ng, M, Shafrir A, Van Tongeren M, Mistry R, Sobey R et al., (2011) IOM research project: P937/100. Health, socio -economic and environmental aspects of possible amendments to the EU Directive on the protection of workers from the risks related to exposure to carcinogens and mutagens at work. SHEcan summary report. Edinburgh EH14 4AP, UK: Institute of Occupational Medicine.

Collingwood S, Heitbrink WA. (2007) Field evaluation of an engineering control for respirable crystalline silica exposures during mortar removal. *J Occup Environ Hyg*; 4: 875–87.

Croteau GA, Flanagan ME, Camp JE *et al.* (2004) The efficacy of local exhaust ventilation for controlling dust exposures during concrete surface grinding. *Ann Occup Hyg*; 48: 509–18.

Croteau GA, Guffey SE, Flanagan ME *et al.* (2002) The effect of local exhaust ventilation controls on dust exposures during concrete cutting and grinding activities. *AIHA J (Fairfax, Va)*; 63: 458–67.

Echt A, Sieber WK. (2002) Control of silica exposure from hand tools in construction: grinding concrete. *Appl Occup Environ Hyg*; 17: 457–61.

English Heritage. (2012) *Practical building conservation: stone masonry*. Surrey, Canada: Ashgate Publishing.

Flanagan ME, Seixas N, Becker P *et al.* (2006) Silica exposure on construction sites: results of an exposure monitoring data compilation project. *J Occup Environ Hyg*; 3: 144–52.

Flanagan ME, Seixas N, Majar M *et al.* (2003) Silica dust exposures during selected construction activities. *AIHA J (Fairfax, Va)*; 64: 319–28.

Forastiere F, Goldsmith DF, Sperati A *et al.* (2002) Silicosis and lung function decrements among female ceramic workers in Italy. *Am J Epidemiol*; 156: 851–6.

Garcia A, Jones E, Echt E, Hall R. (2006) *In-depth survey report of a local exhaust ventilation device for suppressing respirable and crystalline silica dust from powered saws at Revelation Roofing, Denver, CO. NIOSH*. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Division of Applied Research and Technology.

Health and Safety Executive (HSE). (2001) Controlling exposure to stonemasonry dust HSG201. ISBN 978 0 7176 1760 9. Available at http://www.hse.gov.uk/pubns/priced/hsg201.pdf. Accessed 9 September 2012.

Health and Safety Executive (HSE). (2005) MDHS 101, Crystalline silica in respirable airborne dust, direct on filter analyses by IR spec and X ray diffraction. The UK Health and Safety Executive. Available at http://www.hse.gov.uk/pubns/mdhs/pdfs/mdhs101.pdf. Accessed September 2014.

Health and Safety Executive (HSE). (2009) Silica baseline survey RR689. Available at http://www.hse.gov.uk/research/rrpdf/rr689.pdf. Accessed 20 November 2012.

Health and Safety Executive (HSE). (2011) Controlling airborne contaminants at work, a guide to local exhaust ventilation (LEV). ISBN 978 0 71766 4153. Available at http://www.hse.gov.uk/pubns/priced/hsg258.pdf. Accessed 10 February 2013.

Healy C, Coggins M, Van Tongeren M *et al.* (2013) Respirable crystalline silica exposures among stone workers in Ireland. In Harper M,Lee T, editors. *Silica and associated respirable mineral particles, STP 1565*. West Conshohocken, PA: ASTM International, pp. 39–53. doi:10.1520/STP156520120219.

Healy CB, Coggins MA, Van Tongeren M *et al.* (2014) Determinants of respirable crystalline silica exposure among stoneworkers involved in stone restoration work. *Ann Occup Hyg*; 58: 6–18.

Hornung RW, Reed LD. (1990) Estimation of average concentration in the presence of nondetectable values. *Appl Occup Environ Hyg*; 5: 46–51.

International Agency for Research on Cancer. (1997) IARC working group on the evaluation of carcinogenic risks to humans: silica, some silicates, coal dust and para-aramid fibrils. Lyon, 15–22 October 1996. *IARC Monogr Eval Carcinog Risks Hum*; 68: 1–475.

Landrigan PJ, Cherniack MG, Lewis FA *et al.* (1986) Silicosis in a grey iron foundry. The persistence of an ancient disease. *Scand J Work Environ Health*; 12: 32–9.

Leung CC, Yu IT, Chen W. (2012) Silicosis. *Lancet*; 379: 2008–18.

McBride EF. (1985) *Diagenetic processes that effects provenance determination in sandstone*. Netherlands: Springer, pp. 95–114.

Middaugh B, Hubbard B, Zimmerman N *et al.* (2012) Evaluation of cut-off saw exposure control methods for respirable dust and crystalline silica in roadway construction. *J Occup Environ Hyg*; 9: 157–65.

Occupational Safety and Health Administration (OSHA). (2013) Occupational exposure to crystalline silica proposed rule. Available at https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=23900. Accessed September 2014.

Oxman AD, Muir DC, Shannon HS *et al.* (1993) Occupational dust exposure and chronic obstructive pulmonary disease. A systematic overview of the evidence. *Am Rev Respir Dis*; 148: 38–48.

Pettijohn FJ, Potter PE, Siever R. (1987) *Sand and sandstone*. New York: Springer.

Phillips ML, Johnson DL, Johnson AC. (2013) Determinants of respirable silica exposure in stone countertop fabrication: a preliminary study. *J Occup Environ Hyg*; 10: 368–73.

Rosenman KD, Reilly MJ, Rice C *et al.* (1996) Silicosis among foundry workers. Implication for the need to revise the OSHA standard. *Am J Epidemiol*; 144: 890–900.

Scientific Committee on Occupational Exposure Limits (SCOEL). (2002) *Recommendation from the Scientific Committee on Occupational Exposure Limits for Silica, Crystalline (respirable dust), SCOEL/SUM/94-final*, June 2002.

Shepherd S, Woskie SR, Holcroft C *et al.* (2009) Reducing silica and dust exposures in construction during use of powered concrete-cutting hand tools: efficacy of local exhaust ventilation on hammer drills. *J Occup Environ Hyg*; 6: 42–51.

Siemiatycki J, Dewar R, Lakhani R *et al.* (1989) Cancer risks associated with 10 inorganic dusts: results from a case-control study in Montreal. *Am J Ind Med*; 16: 547–67.

Simcox NJ, Lofgren D, Leons J *et al.* (1999) Silica exposure during granite countertop fabrication. *Appl Occup Environ Hyg*; 14: 577–82.

Thorpe A, Ritchie AS, Gibson MJ *et al.* (1999) Measurements of the effectiveness of dust control on cut-off saws used in the construction industry. *Ann Occup Hyg*; 43: 443–56.

Tjoe Nij E, Hilhorst S, Spee T *et al.* (2003) Dust control measures in the construction industry. *Ann Occup Hyg*; 47: 211–8.

West G. (1989) Rock abrasiveness testing for tunnelling technical note. *Int J Rock Mech Min Sci*; 26: 151–160.

Woskie SR, Kalil A, Bello D *et al.* (2002) Exposures to quartz, diesel, dust, and welding fumes during heavy and highway construction. *AIHA J (Fairfax, Va)*; 63: 447–57.