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Determination of respirable-sized crystalline silica in different ambient environments in the United Kingdom with a mobile high flow rate sampler utilising porous foams to achieve the required particle size selection

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A B S T R A C T

Inhalation of respirable crystalline silica (RCS) can cause diseases including silicosis and cancer. Levels of RCS close to an emission source are measured but little is known about the wider ambient exposure from industry emissions or natural sources. The aim of this work is to report the RCS concentrations obtained from a variety of ambient environments using a new mobile respirable (PM_4) sampler. A mobile battery powered high flow rate (52 L min^{-1}) sampler was developed and evaluated for particulate aerosol sampling employing foams to select the respirable particle size fraction. Sampling was conducted in the United Kingdom at site boundaries surrounding seven urban construction and demolition and five sand quarry sites. These are compared with data from twelve urban aerosol samples and from repeat measurements from a base line study at a single rural site. The 50% particle size penetration (d_{50}) through the foam was 4.3 µm. Over 85% of predict bias values were with ± 10% of the respirable convention, which is based on a log normal curve. Results for RCS from all construction and quarry activities are generally low with a 95 th percentile of 11 µg m^{-3}. Eighty percent of results were less than the health benchmark value of 3 µg m^{-3} used in some states in America for ambient concentrations. The power cutting of brick and the largest demolition activities gave the highest construction levels. Measured urban background RCS levels were typically below 0.3 µg m^{-3} and the median RCS level, at a rural background location, was 0.02 µg m^{-3}. These reported ambient RCS concentrations may provide useful baseline values to assess the wider impact of fugitive, RCS containing, dust emissions into the wider environment.

1. Introduction

Crystalline silica is an abundant mineral found in many clays, rocks and sands and is widely used in building materials, ceramics, chemicals, glass and metallurgical industries (Moore, 1999). In the workplace, the health related particle size range of interest for airborne crystalline silica measurements is termed the 'respirable' fraction i.e. particles that can penetrate deep into the gas-exchange regions of the lung. Respirable refers to a size range containing particles mostly less than 16 µm and is derived from a cumulative log normal distribution with a 50% penetration cut-off aerodynamic diameter (d_{50}) of 4.00 µm (EN 481, 1993). The respirable dust fraction has a similar target d_{50} value to an environmental particle size fraction referred to as PM_4. PM_4 has a d_{50} penetration value that lies between particle size fractions of $PM_{2.5}$ (d_{50} at 2.5 µm) and PM_{10} (d_{50} at 10 µm) more commonly employed in ambient air monitoring programs.

Exposure by inhalation to respirable crystalline silica (RCS) particles is a hazard encountered by those working with materials in construction and quarry industries and can result in a range of adverse health effects including silicosis (NIOSH, 2002) and lung cancers (IARC, 2012). In a retrospective study it was estimated that around 900 cases of occupational cancers in Great Britain in 2004 were attributable to exposure to RCS (Rushton et al., 2012). Crystalline silica is a common constituent of many natural and building materials and emissions of dust may also result in background exposures. In the United States (US) of America, an annual running population health benchmark exposure value of 3 µg m^{-3} expressed as a PM_4 fraction, has been derived, in some states, for example, by California's Office of Environmental Health Hazard Assessment (2005) and in Minnesota, by their Department of Health (MDH, 2017) for the monitoring of sand extraction activities (MDH, 2017). This benchmark value is based on an evaluation conducted by the US Environmental Protection Agency (EPA, 1996) and is an average value estimated from PM_{10} sampling data at which there is thought to be little or no risk to the wider populous. RCS concentrations of 10 µg.m^{-3} are also significant because they are potentially detectable (for an 8 h sample) with the personal respirable sampling

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equipment used in routine occupational hygiene monitoring of workers that operate between 2 and 10 L min^{-1}.

The aim of this article is two-fold. Firstly, to present information on the development of an aerosol sampler that employs foams of known porosity to achieve the desired respirable (PM_4) particle size cut. Foams provide a low cost and light weight modification as an insert into the inlet of an existing sampler (Kenny et al., 2001a). They provide a mechanism to select a smaller particle size than is captured by the inlet design and are frequently used in workplace personal exposure sampling (Chen et al. 1998; Aitken et al., 1993 and Kenny and Stancliffe, 1997). A useful attribute of foam systems is that a fraction of particles larger than the respirable fraction (inhalable dust) can also be measured i.e. by summing particles collected on the foam and particles that are collected on the filter. They have also been used for environmental exposure assessment. Mark et al. (1997) modified a personal workplace sampler with a foam insert to collect PM_{10} to assess exposure of the public to atmospheric particulate. Foams were used in a CIS sampler, which has a conical inlet, for the high flow rate (16.5 L min^{-1}) personal sampling of $PM_{2.5}$ (Adams et al., 2001).

The second aim is to present for the first time, measurements of RCS in urban air taken at the fence-line surrounding construction and demolition activities in Great Britain (GB) and to compare them with ambient measurements taken in quarries and at a rural site. Whilst there is abundant information regarding levels of worker exposure to RCS in the immediate vicinity of the emission (Chisholm, 1999; Lumens and Spee, 2001; Ehrlich et al., 2013; Esswein et al., 2013) in contrast, there is a paucity of information regarding measured concentration of RCS in the wider urban air environment. Fugitive dust emissions from construction activities are generally poorly quantified in global and national emissions estimates (Font et al., 2014), and lack comprehensive information on their chemical makeup and the RCS content is generally non-existent. There are a number of reasons why this is so: limit values for RCS in ambient air do not exist in many countries; measurements require specialised analytical facilities equipped with X-ray diffraction (XRD) instrumentation and there are no consensus on what particle size fraction (i.e. $PM_{10/4/2.5}$) should be collected, unlike the workplace environment where respirable sampling is an established approach.

Some ambient aerosol studies have been done. Davies et al. (1984) measured crystalline silica in the in cities in California and found up to 1.9 µg m^{-3} in the fine ($PM_{2.5}$) and between 1 and 8 µg m^{-3} in the course (PM_{10}). In Rome, average weekly concentration values of crystalline silica in the PM_{10} size fraction were reported as between 0.6 and 1.5 µg m^{-3} (Puledda et al., 2003) and between 0.3 and 2.9 µg m^{-3} (De Berardis et al., 2007). Increased silica concentrations were found to coincide with southerly winds suggesting that the periodic influx of sand particles transported from the Sahara was a contributing factor. Monitoring studies just beyond the fence line, at industrial locations have also been reported. Richards et al. (2009) measured ambient RCS (as PM_4) around three Californian sand and gravel plants and reported downwind values in the range 0.3–2.8 µg m^{-3}. Richards and Brozell (2015) achieved slightly lower RCS values for PM_4, when sampling for 24 h, around five sites producing sand for the fracking industry in Wisconsin (Range of geometric means 0.22–0.36 µg m^{-3}, maximum 1.1 µg m^{-3}) Peters et al. (2017) conducted respirable sampling at homes within 800 m of quarries extracting sand for fracking operations. Levels of exposure near seventeen homes were generally, less than 0.4 µg m^{-3}. Some higher RCS concentrations were found (15–37 µg m^{-3}) from some long term samples (less than three percent) when wind velocities were also elevated. Higher crystalline levels from PM_{10} samplers (4–19 µg m^{-3}) were found when monitoring mine tailings depots in South Africa containing 70–90% crystalline silica (Andraos et al., 2018). The mine tailing sites had a substantial proportion of ultrafine particles and the rainfall was limited (less than 130 mm each month).

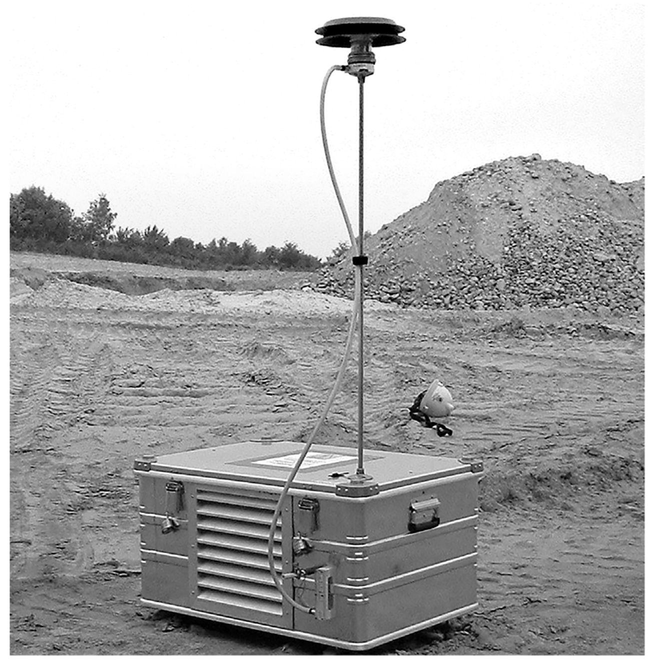

Fig. 1. The HSE high flow rate mobile environmental respirable dust sampler in position at a quarry.

2. Experimental

2.1. Aerosol sampler development and validation

The aerosol sampler used in the work, shown in Figs. 1 and 2, was designed and constructed at the Health and Safety Executive's laboratory. Two heavy duty leisure lead acid batteries were used to power a rotary vane pump (Rotheroe and Mitchell L60 model) allowing a nominal flow rate of 50 L min^{-1} for a period of up to 12 h. Extended sampling operations using mains power supply were also possible. To achieve the desired respirable particle selectivity, a foam separator system was developed which consisted of a sandwich of a 20 mm thick reticulated polyurethane foam disk (45 pores per inch porosity) and a 10 mm thick foam disk (60 pores per inch porosity). The specifications for this foam separator were derived from the use of an empirical model developed by Kenny et al. (2001b) and subsequently validated by challenging representative foam separators with a test aerosol of glass microspheres of known median diameter in accordance with procedures set out in EN 13205-2 (CEN, 2014). The d_{50} and the fractional penetration for the whole particle size distribution penetrating the foam particle selector were calculated and modelled. Further details are provided in Supplementary Information S1. The differences between the fitted performance curve and the target respirable convention were used to calculate sampler bias for an array of challenge size distributions, described in EN 13205:2 (CEN, 2014). A bias map was developed for each theoretical challenge dust to assess how closely the sampler would agree with the sampling convention for a range of exposure scenarios (Görner et al., 2001). The respirable dust fraction that penetrates the foam was subsequently collected onto a 2 µm pore size 60 mm diameter mixed cellulose ester (MCE) filter, which was selected as it ashes easily thus facilitating the recovery of RCS during subsequent analysis.

2.2. Sampling at quarry sites

Five quarries in England and Wales that handle quartz sand or sandstone were surveyed. The sites were selected because they employed good dust suppression techniques (e.g. wetting of lorry tyres).