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A mechanism for the production of ultrafine particles from concrete fracture☆

Nassib Jabbour [a], E. Rohan Jayaratne [a], Graham R. Johnson [a], Joel Alroe [a], Erik Uhde [d], Tunga Salthammer [d], Luke Cravigan [a], Ehsan Majd Faghihi [a], Prashant Kumar [b, c], Lidia Morawska [a, *]

[a] International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Australia
[b] Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom
[c] Environmental Flow (EnFlo) Research Centre, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom
[d] Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, 38108 Braunschweig, Germany

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ABSTRACT

While the crushing of concrete gives rise to large quantities of coarse dust, it is not widely recognized that this process also emits significant quantities of ultrafine particles. These particles impact not just the environments within construction activities but those in entire urban areas. The origin of these ultrafine particles is uncertain, as existing theories do not support their production by mechanical processes. We propose a hypothesis for this observation based on the volatilisation of materials at the concrete fracture interface. The results from this study confirm that mechanical methods can produce ultrafine particles (UFP) from concrete, and that the particles are volatile. The ultrafine mode was only observed during concrete fracture, producing particle size distributions with average count median diameters of 27, 39 and 49 nm for the three tested concrete samples. Further volatility measurements found that the particles were highly volatile, showing between 60 and 95% reduction in the volume fraction remaining by 125 °C. An analysis of the volatile fraction remaining found that different volatile material is responsible for the production of particles between the samples.

1. Introduction

Airborne particles originate either as primary particles that are emitted directly from a source or secondary particles that are produced in the air by the condensation of vapours emitted by the source (Colbeck, 2014). Examples of primary particles are carbon soot particles emitted by motor vehicles and industrial sources, windblown mineral dust and salt nuclei that originate from sea spray during the breaking of ocean waves. Secondary particles are produced from precursor gases which condense to form liquid droplets. A common example in the atmosphere is sulphur dioxide that is oxidised to sulphuric acid gas which readily condenses to form volatile liquid droplets. Generally, most primary particles are solid, while secondary particles are liquid. At the time of emission/formation, primary particles are usually larger than secondary particles. Particles originating from combustion processes consist of both primary particles in the form of soot as well as secondary particles that are formed from the gaseous products (Kumar et al., 2013). On the other hand, mechanical processes such as cutting, crushing and rubbing are known to generate only primary particles directly from the source (Azarmi et al., 2014).

It is well known that coarse particles originate from mechanical activities such as fracturing and crushing of building materials. These particles are generally larger than those classified as fine particles (<2.5 μm). The only known exception is the fracture of polymers containing nanocomposite materials. For example, recent research by Sachse et al. (2012) has shown that the mechanical drilling of silica-based polyamide 6 nanocomposites is accompanied by the emission of large numbers of ultrafine particles. Van Broekhuizen et al. (2011) reviewed a number of mechanical processes involving engineered nanomaterials that resulted in the emission of ultrafine particles. Ogura et al. (2013) studied the

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* Corresponding author.
E-mail address: l.morawska@qut.edu.au (L. Morawska).

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release of carbon nanotubes during the grinding of polystyrene-based composites and listed a number of other studies that have reported release of nanofibers from composite materials as a result of mechanical processes such as cutting, drilling, sanding and grinding.

Particle pollution from construction activities impacts not just the surrounding areas but the greater urban environment, particularly in megacities of countries with growing economies. For example, according to the China Daily (http://www.chinadaily.com.cn/china/2014-02/19/content_17292881.htm) there are presently over 5000 construction sites in Wuhan, China and the city is expected to invest 2 trillion yuan (US$329 billion) in urban construction over the next five years. The impact of this on the urban environment will be quite significant (Faber et al., 2015). In regards to the associated health effects, it is well known that smaller particles have a greater impact than coarse particles, as they can penetrate deeper into the lungs during inhalation. Recently, there has emerged evidence for the release of ultrafine particles during mechanical processes involving the fracturing of non-composite concrete. Asadi et al., (2012) found large concentrations of nanoparticles during asphalt and concrete preparation activities such as mixing, pouring and compaction. Approximately 49% of the particles by number were in the smallest size category – between 10 and 30 nm. Kumar, Mulheron, and Som (2012), using a fast-response differential mobility spectrometer, monitored particle number concentration and size distribution in a confined room in the presence of simulated building activities including crushing of concrete in a mixer and fracturing of concrete blocks with a lump hammer. All processes were accompanied by elevated concentrations of ultrafine particles in a tri-modal size distribution with peaks corresponding to fresh nuclei (<10 nm), nucleation mode (10–30 nm) and accumulation mode (30–300 nm). Later, Kumar and Morawska (2014) observed up to 93% of particles by number in the ultrafine size range during the recycling of concrete and further work exhibited the similar observations during cutting, drilling and mixing of concrete (Azarmi et al., 2014). The observation of ultrafine particle emissions during the fracture of concrete is contrary to our conventional knowledge of aerosol physics where, as shown above, ultrafine particles are not usually produced by purely mechanical means. The study opened up a number of pertinent questions regarding the mechanism of production of these ultrafine particles and their physicochemical characteristics. The objective of the present study was to carry out further research into this phenomenon in order to answer these two questions.

Here, we present a hypothesis that the observed airborne nanoparticles are secondary particles, formed though nucleation. Conventional knowledge suggests that attractive cohesive forces between particles are increasingly difficult to overcome at smaller particle sizes and that the simple mechanical fracture of primary particles is effectively limited to sizes greater than approximately 500 nm (Hinds, 2012). Mechanical fracture would be more likely disperse any ultrafine material into comparatively large clusters of primary particles producing an aerosol size distribution exhibiting a peak in the low micrometer size range. Smaller clusters of primary particles below 500–700 nm in diameter would also be present in the aerosol but their concentrations would decrease significantly with decreasing cluster size (Corn, 1961a, 1961b). We hypothesize that during the fracture process, the temperature of the concrete fissure rises high enough to vaporise semi-volatility species present in the concrete. Once emitted into the atmosphere, these condensable gases would undergo nucleation to form the observed ultrafine particles. This study aimed to derive evidence for such a physical mechanism and determine the volatility and chemical nature of the nanoparticles emitted during the fracture of concrete.

2. Methods

This study set out to explore particle production from concrete fracture in a laboratory setting. The initial experiments were designed to determine whether particle formation could be observed from concrete fracture conclusively, using a Scanning Mobility Particle Sizer (SMPS) system and an experimental chamber. Subsequent experiments using a Volatility Tandem Differential Mobility Analyser (VTDMA) characterised the volatility of the particles produced. An alternate particle production method was attempted using an electric furnace. Gas Chromatography mass spectrometry (GC/MS) was used for bulk concrete sample analysis, to determine the presence of volatile material in the samples. A control study was also conducted to establish whether external containments were responsible for the observed particle production.

2.1. Concrete composition

The concrete samples chosen for the study were based on materials typically used by industry and consumers for building and construction in Australia and the UK, rather than a mix specifically developed for this project. Three different samples were used, termed RC (research concrete), RSC (rapid set concrete) and CMLC (construction materials laboratory concrete). The RC sample was freshly made high strength research concrete provided by the QUT Civil Engineering Department. The RSC sample was purchased commercially from a local hardware store (Bastion™ Rapid Set Concrete, Bunnings Warehouse®), and also provided by the QUT Civil Engineering Department. The CMLC sample was provided by the Construction Materials Laboratory (CML) at the University of Surrey, conforming to the same standards as the previous study by Kumar et al. (2012). The RC and RSC sample dimensions followed Australian concrete test cylinder standards at 100 mm in diameter by 200 mm in length. The samples obtained from the CML were 100 × 100 × 40 mm.

2.2. Apparatus

All testing was conducted inside a 1 m^3 experimental chamber, which was kept at a slight overpressure to ensure that it was not contaminated by ambient air. This was achieved using compressed air pumped into the chamber through HEPA filters. The input window on one side was modified to accommodate a conductive bag to allow access to the chamber while maintaining the seal. The sampling tubes were placed at the opposite end with their inlets covered with paper towel serving as a filter to stop excessive numbers of coarse particles entering the measurement equipment. A small fan was placed inside the chamber to facilitate mixing.

Particle size distribution (PSD) measurements were conducted with an SMPS, a system which combines a condensation particle counter (CPC), a TSI 3071a Electrostatic Classifier (EC) and a Kr^{85} Neutraliser (TSI, Shoreview, MN). Two CPCs were used, a TSI 3010 butanol based CPC or a TSI 3787 water based CPC. Across all experiments, particle concentrations were measured with either 3010 or 3787 TSI CPCs, having size ranges of 10–300 nm and 5–300 nm, respectively.

Measurements of particle volatility were conducted with a VTDMA, an apparatus ensemble of two TSI 3010 CPCs and two TSI 3071a ECs in conjunction with a TSI thermodenuder. The VTDMA preselected particles of the required size, which were passed through a thermodenuder set at a certain temperature. The effect of this heating process was observed through the resulting PSD, acquired with the second EC.

Samples were heated in an electric furnace and the gases and