The exposure to coarse, fine and ultrafine particle emissions from concrete mixing, drilling and cutting activities

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Graphical Abstract

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Research highlights

- ▶ Particle number and mass emissions from mixing, drilling and cutting are measured.
- ▶ Emission factor and exposure during these simulated activities are estimated.
- ▶ Average PNC were 4–15 times higher over the background PNC during the activities.
- ▶ Average exposure doses varied up to about 38–times during the studied activities.
- ▶ Negligible fraction of PNCs for particles >300 nm was found during all activities.

ABSTRACT

Building activities generate coarse ($PM_{10} \leq 10 \mu m$), fine ($PM_{2.5} \leq 2.5 \mu m$) and ultrafine particles ($<100 \text{ nm}$) making it necessary to understand both the exposure levels of operatives on site and the dispersion of ultrafine particles into the surrounding environment. This study investigates the release of particulate matter, including ultrafine particles, during the mixing of fresh concrete (incorporating Portland cement with Ground Granulated Blastfurnace Slag, GGBS or Pulverised Fuel Ash, PFA) and the subsequent drilling and cutting of hardened concrete. Particles were measured in the 5–10,000 nm size range using a GRIMM particle spectrometer and a fast response differential mobility spectrometer (DMS50). The mass concentrations of $PM_{2.5-10}$ fraction contributed ~52–64% of total mass released. The ultrafine particles dominated the total particle number concentrations (PNCs); being 74, 82, 95 and 97% for mixing with GGBS, mixing with PFA, drilling and cutting, respectively. Peak values measured during the drilling and cutting activities were 4 and 14 times the background. Equivalent emission factors were calculated and the total respiratory deposition dose rates for PNCs for drilling and cutting were $32.97 \pm 9.41 \times 10^8 \text{ min}^{-1}$ and $88.25 \pm 58.82 \times 10^8 \text{ min}^{-1}$. These are a step towards establishing number and mass emission inventories for particle exposure during construction activities.

Key words: *Exposure rate; Emission factor; Particulate matter; ultrafine particles; Concrete mixing; Drilling and cutting*

1. INTRODUCTION

Exposure to ultrafine particles ($<100 \text{ nm}$) and particulate matter (PM) is of great concern to the air quality management community due to their potential adverse impacts on human health and the environment [1, 2]. There is substantial epidemiological and toxicological evidence to suggest that it is important to evaluate the influence of both particle number concentrations (PNCs) and particle mass concentrations (PMCs) on human health [3, 4]. Particle size is important as smaller

particles can penetrate deeper into the respiratory system increasing the potential to adversely affect health [5]. Some studies have speculated that when considering exposure to ultrafine particles, the PNC is a more important exposure metric than any particle mass-based metric [6].

Within urban environments there are a number of sources of ultrafine particles and PM. Ultrafine particles are generally represented by the PNCs whilst the PM₁₀, PM_{2.5} or PM₁ (i.e. those below ≤ 10 , ≤ 2.5 , ≤ 1 μm in aerodynamic diameter, respectively) based on the PMCs [7]. Vehicle emissions are well established as a significant source of PNCs [8, 9] whilst road dust is a major source of PMCs [10]. At the same time, many building activities associated with the creation and management of urban infrastructure also emit particles across the range of PM₁₀ and PM_{2.5} [11]. For example, the effect of PM₁₀ arising from building and road works in and around London was investigated by Fuller and Green [12]. These fugitive emissions found to breach daily mean concentrations of PM₁₀ exceeding the European Union (EU) limit value of 50 $\mu\text{g m}^{-3}$ at numerous occasions. Recent work has also indicated the importance of industrial sites (e.g. waste transfer station) as a local primary source of PM₁₀ emissions [13].

There have been a number of studies of PMCs of ambient PM₁₀ in urban areas, but less work has focused on the PM_{2.5} and PM₁ fractions arising from building activities [14] with even less information relating to particles below 100 nm [9]. Whilst research has been undertaken into the effects of ultrafine particles on the environment and health [15], there is currently no legal regulation, or guidelines, for controlling the public exposure to airborne PNCs within the urban environment, including construction sites [7].

Construction activities such as the mixing, drilling and cutting of concrete have the potential to generate coarse (PM_{2.5-10}), fine (PM_{2.5}), very fine (PM₁) and ultrafine particles. The manufacture of fresh concrete typically involves the mixing of coarse and fine aggregates with cement, water and admixtures in a rotating drum mixer generating considerable air-borne dust [7]. Concrete drilling (employing hardened drill bits) is a common activity both at construction sites and within domestic situations and is known to generate coarse and fine particles [16]. Similarly, the cutting of concrete is common during refurbishment, maintenance and demolition activities and can also produce coarse and fine particles. Despite the fact that such activities are undertaken on a daily basis around the globe, surprisingly little is

known about the associated emissions and exposure levels of the particles produced [17-19].

Many studies have experimentally measured particle number and size distributions during manufacturing, handling and usage of engineered nanomaterials [2, 20]. For example, PNCs in the $0.06\text{--}6.36 \times 10^4 \text{ cm}^{-3}$ range were measured during a simulated sanding process. Some studies have also measured emissions of nano-sized particles during different generation methods [21, 22], or their exposure during handling and bagging processes at workplaces [23, 24]. However, most of these studies are related to *engineered* nanomaterials and there are hardly many investigations that deal with the construction and demolition processes.

There are a few studies concerned with PM emissions arising from the drilling and cutting of materials such as carbon nanofibre as well as composite and silica based nanocomposites [25], the demolition of structures [26], concrete recycling [7] and other building and road works [12, 27]. A summary of relevant studies is presented in Table 1.

The importance of particle emissions from construction sources is likely to increase as the development of urban infrastructure across the globe is expected to reflect world population growth [19]. In addition, there remain significant uncertainties concerning exposure risk because the particles characteristics from construction sources may be different from other, more established sources such as vehicle exhaust [28-31] and non-vehicle exhaust sources [9, 32]. None of the studies to date have presented coarse, fine and ultrafine particles emissions and associated exposure to on-site workers from either of the mixing, drilling or cutting activities (see Table 1), which is the focus of this study.

Taking advantage of research gaps and in continuation of our previous efforts [7, 9, 19, 33] this work investigates the release of particles in the 5–10,000 nm range from three (simulated) construction activities (concrete mixing, drilling and cutting) carried out under controlled conditions in indoor laboratory environment. The objectives were to analyse the size distributions and proportions of both particle number and mass concentrations in the studied size range, compute emission factors (EFs) and exposure to on-site workers.

2. Methodology

2.1 *Experimental setup*

Experiments were conducted to measure the release of PM₁₀, PM_{2.5}, PM₁ and ultrafine particles arising from the manufacture of fresh concrete (mixing), and subsequent processing of hardened concrete by drilling and cutting. The aim of the experiments was to simulate the activities that occur on typical construction sites and consider the implications for workers who are exposed to such procedures.

A total of four different experiments were performed: (i) concrete mixing with a blended cement incorporating Portland cement with 35% by weight Ground Granulated Blastfurnace Slag (GGBS), (ii) concrete mixing with a blended cement incorporating Portland cement with 35% Pulverised Fuel Ash (PFA), (iii) the drilling of hardened concrete, and (iv) the cutting of hardened concrete.

During each experiment the measurement of particle emissions was divided into three distinct time periods: (i) the pre-activity baseline (i.e. background levels in the ambient indoor environment), (ii) the simulated activity (carried out over a fixed time to enable the EFs and exposure doses to be estimated), and (iii) the post-activity background level.

The levels of particle emissions arising during each experiment were measured using a differential mobility spectrometer (DMS50) and GRIMM instrument for measurements of number and size distributions in the 5–10,000 nm range (Section 2.2) such that both the particle number and mass concentrations (PM₁₀, PM_{2.5}, PM₁) could be obtained.

Concrete *mixing* was carried out using a rotating drum mixer, manufactured by ELE International (model: EL34–3540/01, Bedfordshire, United Kingdom), with a 100 litre capacity operating at 60 rpm. Two different concrete mixes were manufactured using the mix specification shown in Supplementary Information (SI) Table S1 incorporating Portland cement blended with either GGBS or PFA. Measurements of particle levels were obtained during the pre-activity and both during the mixing process itself (which took place over a period of ~180–300 seconds) and subsequently during the measurement of the slump test of the resulting fresh concrete mix (see Table 2). Slump test is used at construction sites to measure the workability of freshly made wet concrete. This test was carried out following the method described in BS EN 12350-2. Concrete was filled in a steel slump test cone in three equal layers to measure the “slump (settlement)” of freshly made concrete after lifting up the test cone. The test does not involve any mechanical stresses and the probable source of coarse particles appears to be resuspension of dust from the floor and nano-sized particles from the chemical reactions undergoing in the fresh mix of concrete.

The fresh concrete was subsequently cast into steel moulds (150×150×500 mm) to provide specimens of hardened concrete with known composition for subsequent post-processing drilling and cutting. During this experiment the sampling tube was positioned 1 m away from the source and the DMS50 was allowed to equilibrate, prior to establishing the pre-activity (background) readings (Figure 1). Care was taken to clean the internal tubes of the equipment prior to each experiment and parts of dust deposits from previous experiment.

Dry *drilling* of concrete was carried out using a Kango 501 Rotary Drill with 10 mm masonry drill-bit. A hardened concrete prism (with a characteristic compressive strength equivalent to a grade C_{30/40} concrete) was subject to the creation of a number of 25 cm deep holes, each produced in succession. During the drilling process a water spray was employed to mimic good construction practice and the sampling tube was positioned at 1 m from the source in each case (Figure 1).

Dry *cutting* was carried out on a hardened concrete prism (150×150×500 mm) using a Norton BBL527 model, diamond wheel with a blade shaft speed of 2400 rpm and a 55.88 cm diameter blade of 1.5 mm thickness. Again the sampling point was 1 m away from source (Figure 1).

2.2 Instrumentation

A fast response differential mobility spectrometer (DMS50) was used to measure particles in the 5-560 nm size range. The DMS50 measures particles based on the electrical mobility equivalent diameter (D_p) and has a fast time response of up to 10 Hz for sampling ambient air with and a T_{10-90%} response time of 500 ms. The DMS50 samples air at a rate of 6.5 lit min⁻¹ and further details of working principle of the DMS50 are described in the review by Kumar et al. [30]. The DMS50 provides real-time measurement of particle number spectrum from 5-560 nm sub-divided into 34 channels. The DMS50 has been successfully used in our previous work involving measurements in indoor [7, 19], outdoor [34], in-vehicles [35, 36] and on-board vehicle [37] environments. For quality assurance purposes, the DMS50 was calibrated by the manufacturer and the testing reported here was undertaken within the one year calibration period. The DMS50 was cleaned before each sampling day to remove dust particles accumulated on the electrometer rings. The instrument was set to average the samples every 10 sampling points (i.e. one second sampling rate) to improve the signal-to-noise ratio. Further detail of the DMS50 is presented in Table 3.

A GRIMM particle spectrometer (model 107E) was used to measure the mass distribution of particles per unit volume of air. This instrument utilises a semiconductor laser as the light source. Based on size into appropriate channels,

the signal passes through a multichannel size classifier and finally to a pulse height analyser that classifies signals based on size into appropriate channels. The instrument measures particles mass concentration by an optical size of 0.3–20 μm in 15 different sized channels with a mass concentration range of 0.1–100,000 $\mu\text{g m}^{-3}$. The sensitivity of the instrument is 1 $\mu\text{g m}^{-3}$, and instrument reproducibility is $\pm 2\%$. Ambient air was drawn into the unit every 6 second via an internal volume-controlled pump at a rate of 1.2 lit min^{-1} [38, 39].

A weather station (KESTREL 4500) was used for meteorological measurements (ambient temperature, relative humidity and barometric pressure), which was set up next to the DMS50 and GRIMM instruments. Meteorological information was logged on the Kestrel 4500 at 10 s resolution during all the experiments although wind speed and direction were not recorded since all of the measurements reported here were undertaken in a controlled laboratory environment.

2.3 Emission factors

The emission factors calculated for the various operations investigated were estimated in terms of particle number and mass emissions per unit time (s^{-1}), mass (kg^{-1}) and a combination of both ($\text{s}^{-1} \text{kg}^{-1}$). The net EFs were determined by subtracting the background mass or number concentrations during the “pre-activity (background)” period from the total measured during the “activity” period, see SI Section S1. Using this approach, both the particle number- and mass-based EFs were estimated for all the four activities (mixing with GGBS and PFA, drilling and cutting) across the three of the phases described.

2.4 Estimation of exposure doses for health risk analysis

The analysis of the potential health risk associated with inhalation exposure of PM and ultrafine particles was carried out based on estimated respiratory deposition dose rates. The total dose received by an individual is related to the breathing rate, the period of exposure and the difference between the number of particles inhaled and exhaled during each breath [40]. Including algebraic and semi-empirical deposition models [40, 41], the inhalation and deposition of particles through the respiratory tract can be estimated using fixed or variable deposition fraction (DF) approach, as described in SI Section S2.

3. Results and discussion

3.1 Particle size distributions

The spectrums of particle number distribution (PND) obtained during the simulated building activities are presented in Figures 2a-b (mixing of concrete) and 2c-d (drilling and cutting). It can be seen that during each “activity” period there is a significant change in the PND over background levels. As expected the post-activity levels are lower than those obtained during the activity but were somewhat above the original background reflecting the time taken by particles to disperse after the activity (Section 3.2). For mixing activities undertaken with GGBS and PFA the peak PND values obtained were 2.31×10^4 and $3.80 \times 10^4 \text{ cm}^{-3}$ being ~ 3.0 and 12 -times higher than peak background PNDs, respectively. In terms of nucleation mode particles (those below 30 nm; [42]) and new particle release, peak PNDs produced during mixing with PFA were ~ 1.64 -times higher than those obtained with GGBS. This is thought to reflect the particle size, density and adhesion of the two materials as the mixing process was the same. As seen in Figure 2a-b there is an increase in PNDs in the ultrafine size range during the mixing process.

Figures 2c-d show the PND spectrums obtained during the drilling and cutting of samples of hardened concrete. The peak PND values obtained were 37.10×10^4 and $118.80 \times 10^4 \text{ cm}^{-3}$, respectively, being ~ 3.5 and 8 -times higher than the background peak PNDs. A significant increase in nucleation mode particles was observed with cutting producing a greater release of new particles (over background) than drilling, reflecting the larger surface area of concrete subject to abrasion. These observations confirm that significantly more ultrafine particles are released during cutting and drilling activities in comparison to mixing activities. These results are dissimilar to the findings of Kumar et al. [19], both in terms of peak diameters and the shape of PNDs obtained during their investigations for estimating the release of particles below 100 nm arising from the crushing of hardened concrete cubes, the fracture of concrete slabs and the recycling of concrete debris. For example, their work [19] found peak PNDs at $\sim 20.73 \times 10^4$ and $20.86 \times 10^4 \text{ cm}^{-3}$ during demolition and dry recycling of concrete, respectively, which is ~ 2 - and ~ 6 -times larger to that obtained for the drilling and cutting activities reported here.

3.2 Particle number concentrations

Figures 3 and 4 show the total PNCs and distribution of particles in various size ranges obtained during mixing (with GGBS and PFA), drilling and cutting, respectively. Average PNCs during the activity periods in size ranges 5-30, 30-100, 100-300 and 300-560 nm were $21.27 \pm 2.02 \times 10^3$, $30.97 \pm 16.51 \times 10^3$, $279.11 \pm 61.92 \times 10^3$

and $732.27 \pm 442.51 \times 10^3 \text{ cm}^{-3}$ for mixing with GGBS, PFA, drilling and cutting, respectively. Average PNC values during mixing with GGBS and PFA were ~4 and 15-times above the background levels (Table 4).

The average PNCs during the drilling activity changed relatively little. For example, these were ~1.38-times higher for the second hole than during the first hole (Figure 4a). Average values over the period of drilling periods were ~4-times higher than background level ($69.85 \pm 7.15 \times 10^3 \text{ cm}^{-3}$), as seen in Table 4. For all the activities, the ultrafine size range (below 100 nm) contributed most of the total PNCs. For example, their proportion to total PNCs during the mixing with GGBS, mixing with PFA, drilling and cutting activities was 74, 82, 95 and 97%, respectively (see SI Figure S1). The peak value for the “dry” drilling activity was $5.14 \times 10^5 \text{ cm}^{-3}$ and decreased by ~40% to $3.08 \times 10^5 \text{ cm}^{-3}$ when water spraying was employed as a suppression method since particles are less able to become airborne [43].

The average PNC measured during concrete cutting was $732.27 \pm 442.51 \times 10^3 \text{ cm}^{-3}$, which is ~14-times greater than the background value, Table 4. Taken together Figures 3 and 4 demonstrate that for both the drilling and cutting activities there is an increase in PNC with time and the magnitude of PNC are much higher than occurred during the mixing of fresh concrete. This is thought to reflect the higher rotational frequency, shear stresses and local energy density associated with drilling and cutting activities. These results are comparable with those of Kumar et al. [19] who reported an increase of between 2- and 17-times in the total PNC over the background PNCs for various concrete demolition related activities. After adjusting for background concentrations, the net release of PNCs during cube crushing and ‘dry’ recycling of concrete events were measured as ~ 0.77 and $22.70 (\times 10^4) \text{ cm}^{-3}$, respectively. The corresponding results reported by Kumar et al. [19] were about (2.76, 0.09), (4.02, 0.13), (36.23, 1.22) and (95.06, 3.22) times smaller than values for mixing with GGBS, with PFA, drilling and cutting activities, respectively.

The values of PNC obtained during these processes are not directly comparable but can be put in perspective of the average *roadside* and urban *background* PNCs. The corresponding values of PNCs in European environments were reported as $3.15 \pm 1.60 \times 10^4 \text{ cm}^{-3}$ and $1.63 \pm 0.82 \times 10^4 \text{ cm}^{-3}$, respectively [44, 45], indicating that studied activities may produce particles at levels (above background) that are comparable to, or greater than, those which arise from vehicle exhausts. Given that construction and demolition activities occur within urban areas this raises important questions about the need to understand the associated exposure levels to urban dwellers, building operatives and the need to establish suitable standards and controls.

3.3 Particle mass concentrations

Figure 5 shows the PMC arising from the mixing of concrete with GGBS and PFA. The corresponding average PM_{10} , $PM_{2.5}$ and PM_1 determined during mixing were 1.89×10^3 , 0.78×10^3 , $0.56 \times 10^3 \mu g m^{-3}$ and 1.98×10^3 , 0.94×10^3 , $0.63 \times 10^3 \mu g m^{-3}$, respectively (see SI Figure S2). PMC values showed a rapid increase immediately after the start of mixing. The peak values of PM_{10} , $PM_{2.5}$ and PM_1 reached 4.10×10^3 , 3.65×10^3 and $2.42 \times 10^3 \mu g m^{-3}$ for the concrete containing GGBS. The corresponding values obtained for the mix containing PFA were 3.66×10^3 , 2.35×10^3 and $1.04 \times 10^3 \mu g m^{-3}$, which are many times higher than those for the mixing with the GGBS reflecting the same trend as seen for the PNCs (see Section 3.2).

The results of the drilling and cutting activities show a considerable increase in PMC over background levels. Moreover, the average PM_{10} , $PM_{2.5}$ and PM_1 were calculated as 2.82×10^3 , 1.19×10^3 , $0.80 \times 10^3 \mu g m^{-3}$ for drilling and 3.77×10^3 , 1.34×10^3 , $0.86 \times 10^3 \mu g m^{-3}$ for cutting (Table 5). The peak PMC values of PM_{10} , $PM_{2.5}$ and PM_1 during drilling were 4.94×10^3 , 2.38×10^3 and $1.65 \times 10^3 \mu g m^{-3}$, which are higher than the values of 7.21×10^3 , 2.05×10^3 and $1.26 \times 10^3 \mu g m^{-3}$ for the cutting activity. This substantiates the fact that the cutting activity not only produces more particles, by number (Section 3.2), but also greater particle mass emissions compared with the drilling activity.

Overall, the results in Figure 5 show an increase in the average PMC over background levels during the various activities reflecting the release of new particles. PM_{10} , $PM_{2.5}$ and PM_1 are 32, 58 and 86 times the background during the mixing of concrete with GGBS and 32, 50, 89 times when mixing concrete with PFA. In the same way PM_{10} , $PM_{2.5}$ and PM_1 for the drilling activity were 45, 80 and 115 times the background during the drilling activity, and 50, 80 and 122 times higher during the cutting activity. Depending on the source the values of PMCs varied, however, in all cases the PMC values increased with increasing PNCs (see SI Section S3). It is interesting to compare these results with the work of Hansen et al. [46] who carried out environmental sampling of PM during demolition of a hospital building. They found a 2.9– and 3.3–times increase in concentration for particles higher than $0.5 \mu m$ and $1 \mu m$, respectively. This increase was less marked than that of demolition by implosion [26] which has been shown to be associated with short-term concentrations of PM, 1000-times higher than pre-implosion levels.

3.4 Emission factors

EFs for any activity are calculated in accordance with the method described in Section 2.3. It was made to identify the number and mass of particles being released from the source and to indicate how many particles can be inhaled by an occupant

during the activities. Figures 6 and 7 show the EF based on the concentrations measured at occupational exposure range, within 1 meter. It was shown that the EF not only depends on PNCs and PMC but also depends on volume of the drilled or cut area and on the size and sharpness of the cutting tool. The EFs during the mixing with GGBS, PFA, drilling and cutting activities were $8.25 \pm 4.09 \times 10^4$, $14.95 \pm 7.83 \times 10^4$, $18890.12 \pm 4944.36 \times 10^4$ and $80905.12 \pm 56954.83 \times 10^4 \text{ s}^{-1} \text{ kg}^{-1}$, respectively. Relatively higher EF during mixing with PFA compared with GGBS could possibly be due to the differences in hydration and reaction rates of GGBS and PFA with the Portland cement [47]. The higher EF for cutting compared with drilling is possibly due to the high surface area and rotational frequencies, shear stresses and local energy density associated with cutting. It is worth noting that the EFs are expected to be slightly underestimated, given the fact that the sampling was carried out $\sim 1 \text{ m}$ away from the source, due to a possible dilution between the source and the sampling point. The corresponding values of mass-based EFs for PM_{10} , $\text{PM}_{2.5}$ and PM_1 are presented in SI Table S3.

Generalising the lab results to real site experiments is helpful as they provide a basis to estimate the realistic values of total particle number (or mass) emissions from an individual activity. For instance, the commercial mixers in construction sites produce on average about $30\text{--}40 \text{ m}^3 \text{ h}^{-1}$ (or $20\text{--}27 \text{ kg s}^{-1}$) of concrete, depending on the type of concrete being poured [48]. Assuming an average value of $\sim 35 \text{ m}^3 \text{ h}^{-1}$ (or 23 kg s^{-1}), and the EFs (in $\# \text{ kg}^{-1}$; SI Table S4) for average production of mixers on construction sites gives per unit particle number emission of $\sim 7.98 \times 10^8 \text{ s}^{-1}$ and $14.44 \times 10^8 \text{ s}^{-1}$ during mixing with GGBS and PFA, respectively. Similar estimates can be made for the cutting and drilling activities in order to assess the extent of total particle number emissions from these activities.

3.5 *Exposure assessment*

Measuring the occupational exposure to ultrafine particles and particulate matter at construction sites is subject to several factors, which influence the level of particles exposure. The first is the size range of the measured particles and their concentration. The average dose rates over the activities for particle numbers were estimated using (i) constant DF, and (ii) size-dependant DFs and (as described in Section 2.4). The approach (ii) provided the total deposited doses as $2.35 \pm 0.31 \times 10^8 \text{ min}^{-1}$, $3.40 \pm 2.17 \times 10^8 \text{ min}^{-1}$, $32.97 \pm 9.41 \times 10^8 \text{ min}^{-1}$ and $88.25 \pm 58.82 \times 10^8 \text{ min}^{-1}$ for mixing with GGBS, with PFA, drilling and cutting, respectively (SI Table S5). Figure 8 shows the overall differences between the two approaches. In general, exposure studies using constant DF values can provide a satisfactory approximation of the dose inhaled by commuters. However, an

underestimation of dose can be seen for cases in which the vast majority of inhaled particles are in the nucleation mode (i.e. those below 30 nm in diameter). There is currently no similar data available for direct comparison of our results with other exposure studies. Therefore we have picked the closest possible exposure studies for this purpose. For example, Kumar and Morawska [7] reported results on exposure to airborne particles during simulated concrete recycling activity. The deposited fraction of total PNCs were found to be $24.83 \times 10^8 \text{ min}^{-1}$ during exposure close to the source. Our deposited fraction for mixing with GGBS, with PFA, drilling and cutting was found to be ~ 0.09 , 0.13 , 1.32 , and 3.55 times higher, respectively, compared with those obtained by Kumar and Morawska [7] for concrete recycling. Urban exposure study of Joodatnia et al. [36] estimated the average dose rates over the 30 car journeys in Guildford (UK) using used size-dependant DFs as $5.50 \pm 5.09 \times 10^8 \text{ min}^{-1}$. These come out ~ 0.43 , 0.62 , 5.99 and 16.05 times smaller than those for mixing with GGBS, with PFA, drilling and cutting, respectively. Similarly, Int Panis et al. [49] calculated the dose rate for cycling and car journeys in Brussels (Belgium) by applying a constant DF (0.63) as $9.02 \times 10^8 \text{ min}^{-1}$ and $1.49 \times 10^8 \text{ min}^{-1}$, respectively. These are about (0.26, 1.58), (0.38, 2.28), (3.66, 22.12) and (9.78, 59.22) times smaller than those for mixing with GGBS, with PFA, drilling and cutting, respectively.

4. Summary and conclusion

A DMS50 and GRIMM were used to measure number and size distributions of particles in the 5–10,000 nm size range released by mixing, drilling and cutting activities. The objectives were to understand the number and mass emission characteristics of particles in various size ranges during these simulated building activities, along with estimating the emission factors and exposure of site workers to ultrafine particles and PMs from these activities.

The cutting was found to produce the highest release of new particles in terms of both PNCs and PNDs, followed by the drilling and mixing activities. Overall, the results confirm that the simulated building activities studied here have the potential to release ultrafine particles at levels above that encountered in the normal background. The use of water sprays as a controlling measure worked well to suppress associated dust release.

Ultrafine particles were found to dominate the total PNCs with 74, 83, 95 and 97% during the mixing (with GGBS and PFA), drilling and cutting activities,

respectively, with the highest proportion of ultrafine particles arising from the cutting of concrete. Particles number distributions were dominated by the 5-100 size range during the both drilling and cutting activities. The net average PNC after subtracting the background from the PNCs during the mixing with GGBS, PFA, drilling and cutting activities were found to be 1.60, 2.89, 20.92 and $60.49 \times 10^4 \text{ cm}^{-3}$, respectively, showing up 38-times higher values of average PNCs for cutting activity compared with those for mixing with the GGBS.

The results demonstrate the highest proportion of the total PMCs for coarse particles with 52% during mixing with PFA, and 58, 59 and 64% for the drilling, mixing with GGBS and cutting activities, respectively. The average mass concentration of PM_{2.5} and PM₁ during mixing with GGBS, PFA, drilling and cutting were measured as (780.65, 562.23), (945.30, 636.61), (1193.41, 801.49) and (1345.85, 867.75) $\mu\text{g m}^{-3}$, which shows many times higher values for cutting, and drilling than mixing activities. Particle number based emission rates were estimated as $173.41 \pm 8.43 \times 10^4$, $314.01 \pm 164.55 \times 10^4$, $2266.81 \pm 593.32 \times 10^4$ and $6553.34 \pm 4613.34 \times 10^4 \text{ s}^{-1}$ for mixing with GGBS, PFA, drilling and cutting, respectively, which are much lower than the emission rate obtained from floor sweeping activity as $2 \times 10^9 \text{ s}^{-1}$ [50].

This study has presented hitherto missing information concerning the potential for concrete mixing, drilling and cutting activities to produce ultrafine particles in significant quantities. Further work now needs to be carried out to compare the results of these laboratory based studies with data from real industrial sites and establish the exposure levels that can occur for those carrying out such activities, and those that live or work adjacent to such sites. This has implications both for the owners of buildings and structures and regulatory bodies, who appear to be unaware of the potential for building works to give rise to ultrafine particles at levels significantly above typical background exposures. For filling the research gap, further research is required to understand the physicochemical characteristics and monitor the emission levels of ultrafine particles arising from other construction activities (e.g. refurbishment, demolition, construction sites) within urban areas in order to establish suitable, safe, exposure limits for both on-site workers, and passer-by urban dwellers.

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List of figure captions

Figure 1. Schematic diagram of the experiment set-up, showing instrumentation used and sampling distances; L_c , L_d and L_m represents the length between the DMS50 and the sampling points from cutter, drilling and mixer, respectively. Length of all these sampling tubes is 1 m. Please note that the figure is not to scale.

Figure 2. PNDs for the (a) mixing with GGBS and (b) mixing PFA, (c) drilling, and (d) cutting.

Figure 3. Temporal evolution of PNC and their contour plots during (a) mixing with GGBS, and (b) mixing with PFA.

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Figure 4. Temporal evolution of PNC and their contour plots during (a) drilling, and (b) cutting activities.

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Figure 5. Mass concentration against time for (a) mixing with GGBS, (b) mixing with PFA, (c) drilling, and (d) cutting activities.

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Figure 6. Particle number concentration based EFs for all the four activities. Please note that these are net EFs estimated using the net sum of PNCs (i.e. total during the activity period minus the background PNCs during pre-activity period).

Figure 7. Particle mass concentration based EFs for all the four activities. Please note that these are net EFs estimated using the net sum of PMCs (i.e. total during the activity period minus the background PMCs during pre-activity period).

Figure 8. Respiratory tract deposition dose rate ($\# \text{ min}^{-1}$) calculated using (i) size-dependent DFs and average size-resolved PNCs, and (ii) a constant DF and the average PNC for each activity.

List of Tables

Table 1. Summary of past studies showing measured particle number and mass concentrations from various building activities.

PM Type	Activity type	Instrument used	Size range (μm)	Particle number or mass concentration	Where	Source
PM ₁₀	Wet sawing (cutting carbon nanofibre composite)	DustTrak (model 8520; TSI Inc.)	0.1–10	Mean 60 $\mu\text{g m}^{-3}$	Indoor (National Institute for Occupational Safety and Health, USA)	Mazzuckelli et al. [51]
PNC	Drilling of silica based nanocomposites	CPC +DMA (SMPS+C; Grimm Aerosol)	0.005–0.560	Up to $1.7 \times 10^{11} \text{ m}^{-3}$	Indoor (Tarnamid T30, Azoty Tarnow, Poland)	Sachse et al. [25]
PM ₁₀	Building implosion	Portable nephelometer	0.5–10	Up to 54000 $\mu\text{g m}^{-3}$	Outdoor (22-story building in East Baltimore, USA)	Beck et al. [52]
PM ₁₀	Building demolition	Graseby-Andersen Series 241 Dichotomous PM ₁₀ /PM _{2.5} samplers	2.5–10	Mean 31 $\mu\text{g m}^{-3}$	Outdoor (Three public housing developments in Chicago, USA)	Dorevitch et al. [26]
PM ₁₀	Interaction between tyres and road pavement	TSI DustTrak	0.11–10	Up to 5000 $\mu\text{g m}^{-3}$	Indoor (Road simulator, Swedish National Transport Research Institute, Linköping)	Gustafsson et al. [53]
PM ₁₀	Building and road works	TEOM	2.5–10	Up to 180 $\mu\text{g m}^{-3}$	Outdoor (At over 80 monitoring sites in and around London, UK)	Fuller and Green [12]
PM _{2.5} and PNC	Indoor sources (e.g. floor sweeping)	APS + SMPS + CPC	0.007–20	Median of peak values: 35 $\mu\text{g m}^{-3}$ (PM _{2.5}) 34.9 $\times 10^3$ (PNC)	Indoor (Residential suburb in Brisbane, Australia)	He et al. [50]
PM ₁₀	Concrete grinding	Air-Lites Sampling pumps	0.1–10	Mean 11900 $\mu\text{g m}^{-3}$	Indoor (Laboratory simulation, Ohio, USA)	Akbar-Khanzadeh et al. [54]

Note: DMA = Differential Mobility Analyser; TEOM = Tapered Element Oscillating Micro Balance; SMPS = Scanning Mobility Particle Sizer; CPC = Condensation Particle Sizer; APS = Aerodynamic Particle Sizer

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Table 2. Summary of sampling data during concrete mixing, drilling and cutting activities.

Date	Time	Sampling time (seconds)	Name of activities
03-07-2013	14:40:46 15:27:03	2,777	Mixing with GGBS
04/11/2013	13:28:28 14:39:23	4,255	Mixing with PFA
04/11/2013	14:47:38 15:20:01	1,953	Drilling
04/11/2013	15:37:00 15:41:48	3,888	Cutting

Table 3. Measuring capabilities of DMS50 [2] and GRIMM [38, 39].

DMS50			
Size range (nm)	Sampling rate (s)	Detectable diameter min/max	Measurable concentration range (cm ⁻³)
5–2500	10	5 nm	588 – 2.14×10 ¹²
		2500 nm	9 – 2.33×10 ¹⁰
5–560	0.1	5 nm	8233 – 4.97×10 ¹²
		560 nm	240 – 1.15×10 ¹¹
5–560	1	5 nm	4209 – 4.97×10 ¹²
		560 nm	140 – 1.15×10 ¹¹
5–560	10	5 nm	2628 – 4.97×10 ¹²
		560 nm	72 – 1.15×10 ¹¹
GRIMM			
Size range (nm)	Flow rate (l s ⁻¹)	Measurable concentration range	
0.25–32	0.02	-	10 ³ – 2×10 ⁹

Table 4. Average concentration, Geometrical mean diameter and fractions for particles number during mixing, drilling and cutting activities.

Experiments	Time period	Average $\pm$ STD (# cm ⁻³) $\times 10^3$	Geometrical mean diameter	Ultrafine particles fraction (%)
Mixing with GGBS	Background	5.26 $\pm$ 1.24	58.96 $\pm$ 2.56	68
	Mixing with GGBS	21.72 $\pm$ 2.02	53.01 $\pm$ 2.50	74
	Slump test	11.12 $\pm$ 6.10	35.95 $\pm$ 3.23	78
	Post background	11.88 $\pm$ 2.25	67.49 $\pm$ 2.36	65
Mixing with PFA	Background	1.98 $\pm$ 1.42	63.15 $\pm$ 2.39	66
	Mixing with fly ah	30.97 $\pm$ 16.61	41.93 $\pm$ 2.28	82
	Slump test	8.61 $\pm$ 6.09	34.97 $\pm$ 2.15	88
	Post background	4.08 $\pm$ 1.67	4.08 $\pm$ 1.67	80
Drilling	Background	69.85 $\pm$ 7.15	30.90 $\pm$ 2.34	90
	Drilling	279.11 $\pm$ 61.92	19.55 $\pm$ 2.50	95
	Post background	146.64 $\pm$ 24.35	26.41 $\pm$ 2.33	94
Cutting	Background	127.32 $\pm$ 16.65	27.68 $\pm$ 2.28	93
	Cutting	732.27 $\pm$ 442.51	15.10 $\pm$ 2.17	97
	Post background	233.64 $\pm$ 133.57	23.23 $\pm$ 2.40	93

Table 5. The concentrations of PM₁₀, PM_{2.5} and PM₁ during the activity period. STD and percentage fraction (PF) represent standard deviation and particles fraction of mixing with GGBS, PFA, drilling and cutting, respectively.

		Mixing with GGBS				Mixing with PFA				Drilling			Cutting		
Activities		Back ground	Mixing with GGBS	Slump test	Post Back	Background	Mixing with PFA	Slump test	Post Back	Back ground	Drilling	Post Back	Background	Cutting	Post back
PM ₁₀	Avg	58.45	1891.28	736.12	73.70	61.60	1986.12	846.44	79.63	63.40	2827.27	86.74	74.50	3777.18	89.03
	± STD (µg m ⁻³)	±9.19	±1212.20	±416.50	±60.84	±8.41	±824.44	±335.68	±48.70	±7.47	±820.99	±25.56	±13.547	±2065.46	±50.42
PM _{2.5}	Avg	13.37	780.65	366.44	59.96	18.71	945.30	409.71	62.63	14.98	1193.41	61.25	16.76	1345.85	61.12
	± STD (µg m ⁻³)	±5.46	±769.99	±165.26	±25.43	±14.88	±405.7	±402.17	±28.71	±3.17	±391.18	±13.72	±18.77	±310.474	±28.65
PM ₁	Avg	6.52	562.23	278.27	17.76	7.14	636.61	353.67	18.52	6.95	801.49	18.87	7.12	867.75	21.95
	± STD (µg m ⁻³)	±0.65	±541.26	±40.13	±3.80	±1.99	±48.21	±269.35	±2.16	±2.42	± 228.81	±18.72	±2.55	±172.37	±7.87

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