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Dust formed during drilling in natural stone quarries

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Abstract

Dust mass concentration and concentration decrease was studied in two natural stone quarries in Finland. The dust mass concentrations produced during drilling was measured at several distances with short time interval (5 s) sampling. The variation of concentration was high, and wind direction had a crucial effect on dust dispersion. The impact of weather conditions, such as temperature and relative humidity, on dust concentration were inconsistent. The dust produced during drilling was mainly coarse-grained and it settled quickly. The background mass concentration was attained from 55 to 105 m at the downwind direction from the drill. The fine particle mass concentrations were low during the measurements. The fine particles originated mainly from other, remote, sources and from the machinery used in the quarries. Local dust sources, such as hauling, had a significant impact on dust mass concentrations

even inside the quarry. The drilling capacity effected on dust mass concentration near the drill, but the impact vanished quickly with increasing distance.

Keywords

Drilling
Dust mass concentration
Open pit quarry
Natural stone
Finland

Introduction

Dust is a generic term describing fine, solid particles that are suspended in the atmosphere. Dust is in the micrometer range or larger (Hinds 1999). Total suspended particles (TSP) have relatively coarse size range. TSP size range varies from 10 to 100 μm , but a 30- μm aerodynamic diameter is commonly applied (US EPA 1995). PM_{10} and $\text{PM}_{2.5}$ standards involve particulate matter with an aerodynamic diameter of 10 μm or less and of 2.5 μm or less, respectively. $\text{PM}_{2.5}$ is usually referred to as fine particles (US EPA 1995) and PM_{10} or larger particles to coarse particles. According to the Office of the Deputy Prime Minister, England (2003) particles over 30 μm form the greatest proportion of dust concentration emitted from mineral workings, such as quarries, and will deposit within 100 m from the source. Intermediate sized particles (10–30 μm) are likely to travel up to 200–500 m. Smaller particles (less than 10 μm) represent a small proportion of dust and are deposited slowly (Office of Deputy Prime Minister 2003).

Dust is an environmental issue at many quarries and the most dust producing process in natural stone quarries is drilling (Organiscak and Page 2005; Sairanen 2014). Dust produced during the drilling has decreased during the recent years due to the dust control systems which are today commonly applied (Romu 2014). Blasting produces a dust plume

which spreads over quarry area with the prevailing wind. The quarry area itself and hauling are also significant dust sources (Reed 2003), especially during dry and windy weather conditions.

Dust exposure may correlated with serious health risk. Health effects resulting from exposure to different types of dust include, for example pneumoconiosis, cancer, irritation, and allergic responses such as asthma (World Health Organization 1999). Particle size is directly linked to the potential to cause health problems. Small particles below 10 μm in diameter pose the greatest problems when penetrating deep into lungs and even into bloodstream (US EPA 2013).

Dust particles from quarry operations are observed to have elongated morphology (e.g. Junttila et al. 1997; Hedges 2016). According to Räisänen (2004) the relative proportions of minerals in stone material are not the same as their proportions in the PM_{10} dust, whereas Belardi et al. (2013) observed some correlation between size and morphology of particles and petrographic rock properties. Crystalline silica and quartz have been associated to harmful health effects in several studies (e.g. Madl et al. 2008). Dust formed during the drilling, e.g. in a marble quarry contained approximately 0.2–0.6% crystalline silica (Golbabaei et al. 2004). Hedges (2016) observed that the finer the respirable dust particles the greater proportion of the finer particles, which are crystalline silica.

Dust measurements made in open pit quarries has yielded highly variable results (e.g. Sairanen et al. ~~2016~~2017). The manuscript was published online 5th of January in 2017. Article is still in press. Therefore, studies with similar study setup in varying types of quarries are needed to better understand dust production, concentration variation and dust concentration decrease with increasing distance (i.e. dust retention). This study aims to assess dust production and emission dispersion from rock drilling operation in open pit quarries. This is to achieve a better understanding of dust mass behaviour. Such knowledge is needed to evaluate environmental impact and to prevent harmful effect caused by drilling. Quarrying requires environmental permitting and, therefore, sufficient knowledge of dust and

its dispersion is needed among quarry operators and public officers to ensure the acceptability of the quarrying.

The study was conducted in natural stone quarries, because the amount of drilling is higher compared to, e.g. mining and aggregate quarrying. This paper is framed around the following sub-topics. Firstly, the dust mass concentration produced during the drilling is evaluated from the measurements. Secondly, the differences between the different drill types producing dust, is compared. Thirdly, the impacts of weather conditions (temperature, relative humidity, wind speed) to the dust concentration are discussed. Finally is assessed the retention of dust mass concentration and the distance where background mass concentration is achieved. The health effects caused by dust are excluded in this paper.

Previous studies

Dust measurements in real operating conditions are demanding due to the large amount of variables affecting on dust concentration. The weather conditions, especially wind, have a crucial impact on dust concentration and the dust spreading area. According to previous studies the dust produced during the quarrying consist of coarse particles, which settle near the dust source (Office of Deputy of Prime Minister 2003). However, some studies suggest that the dust particles are spread several kilometres away from the quarries (e.g. Cattle et al. 2012).

The knowledge of dust emissions from quarries is limited and consistency of results is low. A number of studies (Organiscak and Page 1995; Junttila et al. 1996; Aatos 2003; Golbabaie et al. 2004; Organiscak and Page 2005; Olusegun et al. 2009; Bada et al. 2013; Degan et al. 2013; Sairanen 2014) have emphasis on dust formation during the drilling. Dust concentrations from drilling varied between approximately 100 –110,000 $\mu\text{g TSP}/\text{m}^3$ (Sairanen et al. ~~2016~~2017). The manuscript was published online 5th of January in 2017. Article is still in press.

According to Organiscak and Page (1995), TSP caused by drilling varied between 500 and 95,000 $\mu\text{g}/\text{m}^3$ for ten different drills. Three of these drills

had dust control systems having a TSP concentration between 800 and 2000 $\mu\text{g}/\text{m}^3$. The measurements were conducted downwind from 12.2 to 30.5 m of the drill (Organiscak and Page 1995). In a study by Organiscak and Page (2005) drilling produced TSP only 180 and 110 $\mu\text{g}/\text{m}^3$, when dust prevention technique was applied. The measurements were conducted in real operating conditions next to the drill table (Organiscak and Page 2005). In a natural stone quarry in Finland at 50 m distance from the production site the observed PM_{10} and $\text{PM}_{2.5}$ concentrations were approximately 80 and 20 $\mu\text{g}/\text{m}^3$, respectively (Aatos 2003).

Drilling in open pit quarry, where also other quarrying processes (crushing) appeared, had significantly higher dust concentrations: approximately 5000 $\mu\text{g PM}_{10}/\text{m}^3$ (Degan et al. 2013), on average 14,000 $\mu\text{g TSP}/\text{m}^3$ (Junttila et al. 1996) and approximately 16,000 $\mu\text{g PM}_{10}/\text{m}^3$ (Olusegun et al. 2009). The highest reported concentrations were measured in natural stone quarry in Iran, where TSP and PM_{10} concentrations varied 78,000–110,000 and 6000–11,000 $\mu\text{g}/\text{m}^3$, respectively (Golbabaie et al. 2004).

The measurements made in granite quarries in Nigeria (Bada et al. 2013) and in Finland (Sairanen 2014) gained dust mass concentrations same order of magnitude near the drilling. TSP concentrations were few hundreds of micrograms per cubic meter and $\text{PM}_{2.5}$ concentrations were few tens of micrograms per cubic meter in both studies. PM_{10} concentrations had more variation being approximately 70 $\mu\text{g}/\text{m}^3$ in study reported by Bada et al. (2013) and varying between 60 and 670 $\mu\text{g}/\text{m}^3$ in study reported by Sairanen (2014). However, the ambient concentrations measured in Nigeria were significantly higher (approximately ten times or more) than ambient concentrations in Finland even though sampling distance were significantly higher (5000 m) in the study conducted in Nigeria compared to the ambient sampling distances (few tens of meters) in the study conducted in Finland.

Quarrying of natural stone

According to the European standard EN 12670 (2001) (Natural stone—Terminology) natural stone is defined as a piece of naturally occurring rock. A natural stone product is a worked piece of naturally occurring rock used in buildings and for monuments. Natural stone is cut out of solid rock into large solid rectangular blocks with definite dimensions and sizes. The blocks are further processed by sawing and splitting into final products with different surface finishes. Dimension stone and facing stone are other terms often used synonymously for natural stone in architectural purposes.

The Finnish granite quarrying is a mechanized process done by specialized machinery (Selonen and Heldal 2003; Vuolio and Halonen 2010; Salmela et al. 2014). Techniques used comprise precision drilling, smooth blasting, wedging, and diamond wire sawing. The first stage of extraction comprises loosening of the primary block of size from 100 to 4000 m³. At the back of the primary block a line of vertical holes (4–6 m deep) and at the bottom 6–8 m long horizontal holes are drilled with hydraulic drilling machines. The distances between holes are in average 30 cm. Both the vertical and horizontal holes are charged and blasted with plastic cartridges (K-pipes) with a low average charge density. The detached primary block is subdivided into smaller blocks, which are further shaped into final sizes and dimensions, mainly by drilling and hydraulic splitting. The final product of the quarry is a stone block with a definite size and shape.

Materials and methods

Quarries and production devices

Measurements were conducted in two natural stone quarries in Finland. The quarry A is the largest natural stone quarry in Finland with a monthly production of approximately 1800 m³ and the quarry B represents an average Finnish natural stone quarry with a monthly production of approximately 300 m³.

The rock of the quarry A is a brown porphyritic, coarse-grained rapakivi granite with a typical rapakivi texture of round 1–3 cm potassium feldspar

ovoids with a plagioclase mantle. The main minerals are potassium feldspar, plagioclase, quartz, amphibole, and biotite (Härmä and Selonen 2008; Härmä et al. 2015) (Table 1).

Table 1

Properties of the rock types

(Source: Geological Survey of Finland)

Mineral content/technical properties	Quarry A	Quarry B
Amphibole	7.3 wt%	–
Biotite	4.8 wt%	5.2 wt%
K-feldspar	26.9 wt%	39.6 wt%
Muscovite	–	1.3 wt%
Plagioclase	36.9 wt%	22.2 wt%
Quartz	23.1 wt%	30.1 wt%
Accessory minerals	2.0 wt%	1.8 wt%
Water absorption	0.10%	0.12%
Apparent density	2680 kg/m ³	2640 kg/m ³
Flexural strength	9.1 MPa	13.4 MPa
Frost resistance (change of flexural strength)	–4.4%	–3.7%
Compressive strength	162 MPa	171 MPa
Abrasion resistance	17 mm	17 mm

The rock of the quarry B is a medium-grained red porphyritic rapakivi granite mainly composed of potassium feldspar, quartz, plagioclase, and biotite (Lindberg and Bergman 1993; Selonen et al. 2005, 2011) (Table 1). The porphyritic texture of the granite is defined by potassium feldspar phenocrysts (≤ 2 cm in length). A few potassium feldspar ovoids can be found.

Both quarries had following processes running during the dust measurements: drilling, blasting, hydraulic splitting and hauling of stone blocks and leftover stone.

There were two drill types employed in the quarries during the study (Table 2). Drill type 1 (D1) was specially modified from a forest machine to meet the needs of the natural stone production. The drill type 2 (D2) was a commercial drill with higher drilling capacity compared to D1. Drilling was conducted both vertical (V) and horizontal (H) directions (Fig. 1 a, b). All drills were equipped with dust control systems which functioned properly during the measurements.

Table 2

Drill types in operating during measurements

Drill type	Drilling direction	Drilling capacity (m/s)	Other properties
D1V	Vertical	0.14	Modified from forest machine
D2V	Vertical	0.22	Commercial drill
D1H	Horizontal	0.14	Modified from forest machine

Fig. 1

a Vertical drilling with commercial drill (D2V). **b** Horizontal drilling with drill modified from forest machine (D1H) and sampling at downwind (DW) direction at 5 m distance and at side-wind (SW) direction at 10 m distance

Sampling equipment and duration

Measurements were conducted with two Turnkey Osiris nephelometers (Fig. 2a). Nephelometer records continuously and simultaneously particles mass fraction. It detects the light scattered from airborne particles. The scattered light consists of three components: reflection, refraction, and diffraction. The diffracted component depends only on the size of the particle. Osiris nephelometers analyse the light scattered through 10° or

less to respond only to the diffracted component (Turnkey Instruments Ltd 2014) (Fig. 2b).

Fig. 2

a Osiris nephelometer. **b** The nephelometer operating principle (modified from Turnkey Instruments Ltd 2014)

Nephelometer measures four different size categories at the same time: TSP, PM_{10} , $PM_{2.5}$, and PM_1 . The maximum concentration when measuring four different size categories at the same time is approximately $6000 \mu\text{g}/\text{m}^3$, whereas restricting measurement to TSP enables measuring concentration up to $60 \text{ mg}/\text{m}^3$ (Turnkey Instruments Ltd 2009). The Turnkey Osiris nephelometer is standardized for PM_{10} fraction (Turnkey Instruments Ltd 2014).

A sampling interval of 5 s was used in order to observe short time variation in dust emissions. Sampling during the drilling was conducted 3×5 min periods at each sampling point and 180 measurement results for each size fraction measured, were gained from each sampling point. Occasionally, the sampling duration differed from the planned 15 min in total due to the demands of the quarrying processes, such as hauling or when the drilling procedure was completed. There were almost 6000 and 10,500 measurement results in total from quarries A and B, respectively, taken into account in this study.

The sampling during the production was manned. Measurements were conducted at two subsequent days and the background concentration measurements during the night between them. Background concentration measurements were unmanned and sampling interval was 300 s. Longer sampling interval for background concentration measurements was chosen because concentration variation was assumed lower during the night time (Turnkey Instruments Ltd 2009).

Measurement setup

Dust mass concentrations were measured near the drills at different distances at downwind (DW), upwind (UW), and side-wind (SW) direction (see Fig. 3). The measurements were conducted at the same elevation as was the drill. The nearest sampling location 5 m at DW direction remained constant during the measurement. The other sampler was relocated to different distances at different wind directions (Figs. 1 b, 3). The sampling height was 1.5 m which represents breathing height (Fig. 2 a).

Fig. 3

Schematic presentation of measurement setup from the lateral point of view. *DW* downwind, *UW* upwind, *SW* side-wind

The directions and distances of samples varied between quarries and drills measured due to the drilling location properties and the production in the quarry. Quarry benches prevented measurements usually at one direction. The haul roads inside the quarry also restricted the sampling locations. Because of the high mobility in drilling the distance from drilled hole and dust sampler varied during the measurements. The accuracy of the distances was ± 1 m. The lowest variation in distances was when measuring horizontal drilling, due to longer drill holes. The dust samplers were relocated (if possible) when the drilling location shifted. Otherwise, the altering distances were reported in the measurement log sheet.

The background concentrations were measured to control the effect of nearby sources and long distance dust concentrations. The background concentrations were measured inside the quarry near the production measurement site (within few tens of meters) during the night time. The ability to measure background concentration outside the quarry was limited because of the prevailing conditions and safety issues.

Weather conditions

The measurements were conducted during the winter because the applicability of dust prevention techniques is restricted due to freezing water. Dusting during the winter months is the largest due to the low moisture content and ventilation of the air. There was snow on the ground and temperature was below or near 0°C . The snow cover on the ground minimized the effect of the dust emission from the quarry surface. This situation represents the maximum dust emission from production.

The prevailing weather conditions were observed with EasyWeather weather station, which consisted of weather station and recording device (Velleman 2009). The recording device is instructed to be placed indoors. The distance between weather station and recording device is relatively short, not more than approximately 90 m, thus indoor circumstances were unavailable in this study. The winter temperatures caused occasionally interruption in weather monitoring. This was not crucial for the experiment because the duration of production measurement was few hours and the weather conditions stayed relatively stable during the measurements.

The most important weather parameter concerning the scope of this research was the wind direction, which was observed straight from the weather station probe. The weather station monitored temperature, humidity, absolute and relative pressure, wind speed and direction, wind gust speed, and rainfall (Velleman 2009). The average weather conditions were ensured with data gathered from national weather stations located near the quarries A and B. The weather parameters describing average climatic conditions during the measurement are temperature, relative humidity, and wind speed (Table 3).

Table 3

Weather conditions during measurements

Weather parameter	Quarry A	Quarry B
Average temperature (°C)	−4.2 (−5.5 to −3.4)	3.6 (1.6–5.8)
Relative humidity (%)	91 (75 to 96)	75 (66–87)
Wind speed (m/s)	2.7 (1.3 to 4.4)	3.5 (2.2–5.1)
Variation is presented in parenthesis		

The impact of weather conditions on dust mass concentrations were assessed separately for different drill types in different quarries. In this study the results at 5 m distance DW direction are assessed because DW5 measurement point (see Fig. 3) remained the same during the

measurements and there were the largest amount of concentration results available.

Results

The mass concentrations were in general highest at the downwind (DW) measurement points and the lowest measured upwind (UW) from the drill. Dust emissions measured at side-wind (SW) locations were in range between results measured locations for DW and UW (Tables 4, 5). Some incoherent results were obtained due to local dust sources such as hauling. The results are reported separately for each different drill type measured (D1V, D1H, D2V, see Table 2).

Table 4

Coarse particle (TSP and PM₁₀) concentrations (µg/m³) in two natural stone quarries

Wind direction/distance (m)	Quarry A		Quarry B	
	D1V ^a	D2V ^b	D1V ^a	D1H ^c
	TSP/PM ₁₀	TSP/PM ₁₀	TSP/PM ₁₀	TSP/PM ₁₀
DW/5	≥477/≥355	≥916/≥763	31/22	≥487/≥355
DW/10	258/161	180/114	17/12	≥153/≥112
DW/20	106/71	≥561/≥463	9/7	97/61
DW/30	61/41	80/47	–	33/23
DW/40	81/48	–	–	39/25
DW/50	42/29	–	–	56/35
DW/60	–	–	–	57/35
UW/5	620/492	–	15/10	–
≥: Results include measurements exceeding the measurement capacity				
<i>DW</i> downwind, <i>UW</i> upwind, <i>SW</i> side-wind				
^a D1V = drill type 1, vertical drilling, capacity 0.14 m/s				
^b D2V = drill type 2, vertical drilling, capacity 0.22 m/s				
^c D1H = drill type 1, horizontal drilling, capacity 0.14 m/s				

Wind direction/distance (m)	Quarry A		Quarry B	
	D1V ^a	D2V ^b	D1V ^a	D1H ^c
	TSP/PM ₁₀	TSP/PM ₁₀	TSP/PM ₁₀	TSP/PM ₁₀
UW/10	–	9/7	4/4	–
UW/20	–	–	49/34	–
UW/40	–	22/9	–	–
UW/50	11/9	–	–	–
SW/5	221/133	–	–	–
SW/10	–	57/40	–	371/277
SW/35	–	14/10	–	–
SW/50	34/23	–	–	–
≥: Results include measurements exceeding the measurement capacity				
<i>DW</i> downwind, <i>UW</i> upwind, <i>SW</i> side-wind				
^a D1V = drill type 1, vertical drilling, capacity 0.14 m/s				
^b D2V = drill type 2, vertical drilling, capacity 0.22 m/s				
^c D1H = drill type 1, horizontal drilling, capacity 0.14 m/s				

Table 5

Fine particle (PM_{2.5} and PM₁) concentrations (µg/m³) in two natural stone quarries

Wind direction/distance (m)	Quarry A		Quarry B	
	D1V ^a	D2V ^b	D1V ^a	D1H ^c
	PM _{2.5} /PM ₁	PM _{2.5} /PM ₁	PM _{2.5} /PM ₁	PM _{2.5} /PM ₁
DW/5	≥32.6/≥10.4	≥61.9/≥28.7	3.5/0.7	≥34.2/≥7.7
DW/10	28.1/6.2	16.3/4.1	3.4/0.6	13.4/2.5
DW/20	14.3/4.5	52.7/27.4	2.6/0.5	12.7/2.1
DW/30	9.1/3.4	10.4/3.1	—	6.2/1.2
DW/40	14.5/4.7	—	—	6.9/1.3
DW/50	7.9/3.3	—	—	8.3/1.4
DW/60	—	—	—	8.8/1.6
UW/5	32.9/9.9	—	3.2/0.6	—
UW/10	—	4.4/2.2	1.9/0.4	—
UW/20	—	—	6.7/1.1	—
UW/40	—	3.9/1.9	—	—
UW/50	5.6/3.0	—	—	—
SW/5	25.2/6.1	—	—	—
SW/10	—	19.1/6.5	—	31.7/7.4
SW/35	—	5.8/2.6	—	—
SW/50	6.9/3.3	—	—	—
≥: Results include measurements exceeding the measurement capacity				
<i>DW</i> downwind, <i>UW</i> upwind, <i>SW</i> side-wind				
^a D1V = Drill type 1, vertical drilling, capacity 0.14 m/s				
^b D2V = Drill type 2, vertical drilling, capacity 0.22 m/s				
^c D1H = Drill type 1, horizontal drilling, capacity 0.14 m/s				

The highest results exceeded the measuring capacity of the nephelometer, when measuring near the drill (5–20 m distance) at DW direction. High

results for fine particles beyond 5 m were only singular anomalies counting under 0.5% of results. At 5 m DW direction results exceeding the measuring capacity were for both drill D1V in quarry A and drill D1H in quarry B approximately 1%, whereas drill D2V in quarry A gained approximately 4% results exceeding measurement capacity. It seemed that high dust emission was produced particularly when the drilling started and ended and when pulling the drill rod out from the drill hole.

Coarse particles: TSP and PM₁₀

For the coarse particles the results were similar for TSP and PM₁₀ in both quarries. The mass concentration decreases rapidly with increasing distance (Fig. 4) at all wind directions. Decrease was more distinct for TSP compared to PM₁₀ and the most pronounced at the upwind direction (Table 4). TSP concentration was roughly 1.5 times higher than PM₁₀ concentration.

Fig. 4

The PM₁₀ concentrations produced during horizontal drilling at 5 and 10 m distances at downwind in quarry B

Local dust sources like hydraulic splitting, dust handling and hauling affects the results inside the quarry, resulting higher concentrations than measured close to the dust source (Table 4). Higher concentrations than expected were observed 40 m DW in quarry A and 20 m UW in quarry B. In both cases sampling locations had other potential dust sources nearby.

Typical mass concentration variation during the measurements with short (seconds) sampling interval was significant, varying from 1 to over 6000 $\mu\text{g}/\text{m}^3$. The mass concentration measured was quite low in general, but the concentration peaks were high compared to the median level (Fig. 4), which is also supported by statistical analysis. Median mass concentrations were significantly lower compared to average mass concentrations. The average concentrations were approximately 2–5 times higher than the median concentration for coarse particles. To avoid underestimation of dust caused by the quarrying, the average mass concentration was assumed to be more representative compared to the median values. The concentration variances were 3–23 and 4–32% for TSP and PM_{10} , respectively.

DW concentration peaks observed at 5 m distance were also observed later at longer distances (for example 5 and 10 m distance from the drill, see Fig. 4). Concentration peaks descend with increasing distance and at 50 m distance the concentration peaks were only barely distinguished from the altering median level.

Background concentrations in quarries A and B were 11 and 11 $\mu\text{g}/\text{m}^3$ for TSP and 9 and 8 $\mu\text{g}/\text{m}^3$ for PM_{10} , respectively.

Fine particles: $\text{PM}_{2.5}$ and PM_1

Apart from the downwind direction near the drill the fine particle mass concentrations were low for $\text{PM}_{2.5}$ and for PM_1 . The effect of local dust sources (hydraulic splitting, dust handling, and hauling) were also observed for fine particles. The effect was more evident for $\text{PM}_{2.5}$ than for PM_1 . Fine particles mass concentrations decreased also with increasing

distance (Fig. 5) at all wind directions and the decreasing was more pronounced for $PM_{2.5}$ and at UW direction (Table 5). $PM_{2.5}$ concentration was roughly 25% of PM_{10} concentration and PM_1 was under 10% of PM_{10} concentration.

Fig. 5

The $PM_{2.5}$ concentrations produced during horizontal drilling at 5 and 10 m distances at downwind in quarry B

Typical mass concentration variation was significant, varying from between 1 to more than $650 \mu\text{g}/\text{m}^3$. The mass concentration measured was quite low in general, mainly under $25 \mu\text{g}/\text{m}^3$, but the concentration peaks were high compared to the median level (Fig. 5). The variation was similar to the variation of coarse particles, especially for $PM_{2.5}$. Average concentrations were approximately 1–2 times median concentration for fine particles. The concentration variances were 1–19 and 1–35% for $PM_{2.5}$ and PM_1 , respectively.

DW concentration peaks observed at 5 m distance were observed slightly later at longer distances and concentration peaks descend with increasing distance also for fine particles (Fig. 5) as did coarse particles. At 50 m

distance the fine particles concentration peaks were also only barely distinguished from the median level.

Background concentrations in quarries A and B were 5.5 and 2.6 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 2.8 and 0.4 $\mu\text{g}/\text{m}^3$ for PM_1 , respectively.

Mass concentrations during varying weather conditions

All considered weather parameters (temperature, relative humidity, and wind speed) showed unsystematic effect on the mass concentration results. Results were similar for all size categories. As an example, PM_{10} concentrations at 5 m DW are described more detailed below.

Temperature remained relatively constant, within $\pm 5^\circ\text{C}$, during the measurements and it was below 0°C and above it during the measurements in quarry A and quarry B, respectively. Despite the temperature changes, PM_{10} concentration stayed approximately at 470 $\mu\text{g}/\text{m}^3$ in quarry A. In quarry B PM_{10} concentration rose from approximately 380–620 $\mu\text{g}/\text{m}^3$, when temperature rose from 1.6–2.1 to 3.7–5 $^\circ\text{C}$.

Also, the relative humidity showed no effect when measuring drill D1V in quarry A. Instead PM_{10} concentration produced by drill D2V doubled from 600 $\mu\text{g}/\text{m}^3$ to over 1200 $\mu\text{g}/\text{m}^3$, when relative humidity raised from >70–80 to >90%. However, in quarry B the increase in relative humidity from >70–80 to >80–90% decreased PM_{10} concentration from 580 to 290 $\mu\text{g}/\text{m}^3$, respectively.

Decreasing concentration with increasing wind speed was observed when measuring D1V in quarry A and D1H in quarry B. D2V in quarry A had concentration relatively constant with all wind speeds observed during the measurements (Fig. 6).

Fig. 6

PM_{10} concentrations at 5 m distance at downwind direction near different drills with different wind speed

AQ1

The decrease of mass concentration with increasing distance

Dust mass concentration decrease with increasing distance at DW direction was similar for coarse (TSP and PM_{10}) and fine particles ($PM_{2.5}$ and PM_1) (see Tables 4, 5). Therefore, the decrease for PM_{10} and $PM_{2.5}$ represent coarse and fine particles, respectively (Figs. 7, 8).

Fig. 7

PM_{10} concentration at downwind direction in different quarries A and B near different drill types D1H, D1V, and D2V

Fig. 8

PM_{2.5} concentration at downwind direction in different quarries A and B near different drill types D1H, D1V and D2V

Drilling capacity had an effect on dust mass concentration near (at 5 m distance) the drill. The drill D2V with higher (0.22 m/s) drilling capacity gained higher dust mass concentration, approximately $760 \mu\text{g PM}_{10}/\text{m}^3$, at 5 m distance DW compared to drills D1V and D1H with lower (0.14 m/s) drilling capacity, both approximately $360 \mu\text{g PM}_{10}/\text{m}^3$ (see Table 4). The difference with dust mass concentrations was vanished already at 10 m distance, where concentrations were same order of magnitude, roughly $100 \mu\text{g PM}_{10}/\text{m}^3$.

The decrease of mass concentration with increasing distance was evaluated for determining the distance where the background concentrations were achieved. Results from drill D1H in quarry B and drill D1V in quarry A were selected for further analysis, because both drills gained results from several different sampling locations downwind and variation of results was only modest (approximately 10%). Drills D2V from quarry A and D1V from quarry B were excluded from further analysis due to higher variation (approximately 20%) and low dust mass concentration (10 times lower compared to other drills), respectively. Higher variation in D2V results was affected by other dust sources. The low concentration level measured near D1V in quarry B was possibly because of sampling dislocation in relation to wind direction and results were excluded to avoid underestimation. Results for horizontal and vertical drilling are addressed separately in the “Horizontal drilling” and “Vertical drilling”.

The decreasing of dust mass concentration with increasing distance was assessed for DW direction in which the decreasing was the slowest compared to the SW and UW directions. The exponential equation curves for dust retention were determined via the best fitting curve to the measured concentrations of different size categories by Excel.

Horizontal drilling

The horizontal drilling with D1H occurred in isolated location at the upwind direction compared to other production activities operating during the measurements in the quarry B. Therefore, the results of horizontal

drilling were consistent and the inaccuracy of measuring distances were the lowest.

The equations derived for mass concentration retention of coarse particles:

$$C_{TSP} = 235.9 \times e^{-0.034x} \quad 1$$

$$C_{PM10} = 172.0 \times e^{-0.037x}, \quad 2$$

where C_{TSP} is mass concentration of TSP, C_{PM10} is mass concentration of PM_{10} and x is the distance from the drill in meters. According to these equations, the background concentration for TSP and PM_{10} is achieved at distances 90 and 83 m, respectively.

The equations derived for mass concentration retention of fine particles:

$$C_{PM2.5} = 20.18 \times e^{-0.02x} \quad 3$$

$$C_{PM1} = 3.99 \times e^{-0.022x}, \quad 4$$

where $C_{PM2.5}$ is mass concentration of $PM_{2.5}$, C_{PM1} is mass concentration of PM_1 and x is the distance from the drill in meters. The distances where the background concentration are achieved Based on the equations, the background concentration for $PM_{2.5}$ and PM_1 is achieved at distances 102 and 105 m, respectively.

Vertical drilling

The vertical drilling with D1V in quarry A had consistent results and variation was same level as was for the horizontal drilling. The concentration results were in the same order of magnitude compared to other drill types examined.

The equations derived for mass concentration retention of coarse particles:

$$C_{TSP} = 414.3 \times e^{-0.049x} \quad 5$$

$$C_{PM10} = 284.8 \times e^{-0.05x}, \quad 6$$

where C_{TSP} is mass concentration of TSP, C_{PM10} is mass concentration of PM_{10} and x is the distance from the drill in meters. According to these equations, the background concentration for TSP and PM_{10} is achieved at distances 74 and 69 m, respectively.

The equations derived for mass concentration retention of fine particles:

$$C_{PM2.5} = 32.58 \times e^{-0.029x} \quad 7$$

$$C_{PM1} = 8.38 \times e^{-0.02x}, \quad 8$$

where $C_{PM2.5}$ is mass concentration of $PM_{2.5}$, C_{PM1} is mass concentration of PM_1 and x is the distance from the drill in meters. Based on the equations, the background concentration for $PM_{2.5}$ and PM_1 is achieved at distances 61 and 55 m, respectively.

Discussion

Dust mass concentration levels

The majority of dust formed during the quarrying consists on coarse particles (TSP and PM_{10}). Results are in accordance with previous observations (e.g. Office of the Deputy Prime Minister 2003; Cattle et al. 2012). The fine particle mass emissions were low especially for PM_1 , which was mainly under $10 \mu g/m^3$. This implies that fine particles originate largely from other, remote sources and from machinery used in the quarry. Also, the statistical analysis supports this. Coarse particles has the average concentrations 2–5 times higher than the median concentrations, whereas fine particles gain the average concentrations only 1–2 times higher than the median concentrations. High concentration peaks from the production caused higher average concentrations compared to median concentrations of coarse particles.

TSP concentrations measured near the source (5 m) were approximately at the same level (few hundreds of micrograms per cubic meter) as were reported for controlled drills by Organiscak and Page (1995). They observed significant dust retention within few tens of meters, which was perceived also in this study. Bada et al. (2013) reports mass concentration in the same order of magnitude for TSP and $PM_{2.5}$ as measured in this study. Degan et al. (2013), Junttila et al. (1996) and Olusegun et al. (2009) measured approximately ten or more times higher and Golbabaie et al. (2004) approximately 100–200 times higher concentrations compared to this study. Instead Aatos (2003) measured lower concentrations compared to results in this study. Results reported by Aatos (2003) were affected by long sampling distance (50 m). The results in Junttila et al. (1996) and Olusegun et al. (2009) were influenced by other quarrying activities, e.g. crushing. The difference compared to the high concentrations gained by Golbabaie et al. (~~2013~~2004) . The correct year of reference Golbabaie et al. is 2004. Year 2013 is a typo. may have had an influence of the measurement setup.

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The wind direction had a crucial impact on dust mass concentrations and spreading. The concentrations were much lower in the UW and SW direction compared to DW direction, which was expected. Some incoherent results appeared due to other dust sources. Concentrations higher than expected were observed at 40 m DW in quarry A and 20 m UW in quarry B. Incoherent results were measured near hauling (quarry A) and dust handling (quarry B). The high mass concentration at the nearest (5 m) measurement location UW direction (D1V in quarry A) is assumed to be consequence of drilling imparting a momentum to the dust enabling it to overcome the wind, which was also observed by Reed (2003) during haul road dust measurements.

Drilling capacity had an impact on dust mass concentration near (at 5 m distance DW) the drill. The higher drilling capacity equipment (D2V) produced larger amount of dust. Concentration differences vanished quickly with increasing distance and at 10 m distance both vertical drills

D1V and D2V had mass concentration in same order of magnitude, roughly $100 \mu\text{g PM}_{10}/\text{m}^3$. This is assumed to be consequence of the large proportion of coarse particles formed during the drilling, which settle near the dust source.

Impact of weather conditions on dust mass concentration

Weather conditions stayed relatively constant during the measurements. Impacts of weather conditions on results were inconsistent. Temperature had no impact on results when temperature was below 0°C , but when above it, increasing temperature increased dust mass concentration. Correlation was inconsistent between relative humidity and dust concentration. Increasing relative humidity seemed both to increase and decrease mass concentration, when considering different drill types in different quarries. During high wind speed ($>4 \text{ m/s}$) low mass concentrations were measured near D1V in quarry A and D1H in quarry B. Wind speed had no effect on concentration results measured near D2V in quarry A.

Longer sampling periods than applied in this study would enable observations of the concentration level during altering weather conditions. Modest variation in weather conditions is the main reason for the incoherent results. The conditions lacked sufficient variation to cause notable differences. In addition, differing weather conditions appeared in different quarries during measurements of different drill types, which increases the variance in results and, therefore, complicates the ability to observe weather conditions impacts. The chosen climatic conditions (winter) and the observed lack of consistency in weather parameters impacts on dust concentrations confirm the reliability of results representing the dust emission from the natural stone production during similar circumstances.

Distance affecting on dust concentration

Measuring dust mass concentration during the drilling showed that drilling produces mainly coarse dust particles which settle near the dust source. High concentration peaks observed at DW direction were seen both in the nearest sampler (5 m) and other sampler locations (distance 10 m or more). When distance was 50 m or more, the peaks were only barely distinguished from the altering median level. The results reveal the same circumstance which was visible in the quarry area during the measurement: Drilling produces short time dust plumes which travel with a wind and after short period of time dilutes inseparable.

The background concentration of all particle sizes was achieved at 55–105 m distance from the dust source, depending on the drill type and dust size category. The dust retention was more pronounced with larger size categories (TSP and PM_{10}) as they settled nearer the dust source compared to the fine particles. The background concentration was attained 69–90 m distance for coarse particles and at 55–105 m distance for fine particles. Considering the distance where the background concentration is achieved near the natural stone quarries, a generalisation of 100 m is applicable. This rough approximation avoids underestimation in most of the cases. This means that dust mass concentration measurements evaluating quarries dust load to the environment should be conducted at short distances from the quarry boundary or even inside the quarry. The dust concentration can vary strongly during certain weather conditions, but the dust concentration spread over 100 m distances from the source is low due to the ventilating effect of the wind.

Background concentration measurements conducted during the night time may have had an impact on the results. At night the dust concentration is lower due to lack of dust sources, like traffic. This may have caused an underestimation on the background concentration. The background concentration measurements during the night are justifiable to gain measurements during similar weather conditions as production measurements. Longer breaks in the production appear usually in the summertime (mainly in July). The impact of weather conditions when comparing winter and summer time is estimated to be greater than the

impact of background concentration measurement occurring at non-dusty time of the day.

Even though the background concentrations may be underestimated, the background concentrations were reached within 55–105 m distance. This is on the same order of magnitude as Reed's (2003) results, in which the quarry haul road dust concentration reached background concentration approximately at 30 m distance. The certainty of the evaluation of distance in which the background concentration is achieved, is increased by the possible underestimation of background concentration. The generalization of 100 m as a distance where background concentration is achieved is, therefore, applicable concerning dust emission from production for natural stone quarries processing hard rocks.

Conclusions

The dust mass concentrations produced during drilling in natural stone quarries showed large variations due to the local air currents present inside the quarry and the phase of the drilling procedure. Wind direction had a crucial effect on dust dispersion. Increasing wind speed seemed to decrease the dust concentration. The impact of other considered weather conditions, temperature and relative humidity, on dust concentration were inconsistent.

Drilling produces mainly coarse (TSP and PM_{10}) dust particles which settle near the dust source. The fine particle mass concentrations were low, mainly under $25 \mu\text{g}/\text{m}^3$, and they originate mainly from other remote sources and from the machinery used in the quarries.

The drilling capacity effected on dust mass concentration near the drill (approximately 5 m), but the impact vanished quickly with increasing distance (approximately 10 m).

Local dust sources, such as hauling, had a significant impact on dust mass concentrations even inside the quarry. The dust formed in the quarry will

spread approximately at 100 m distance from the dust source after which the dust mass concentration achieves the background level.

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