Dust dispersion in hard rock quarries

Marjo Sitkiä
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Marjo Sitkiä

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Abstract

Open-pit quarrying constitutes a core industry in many countries. Significant dust emissions appear when different types of rock products, such as aggregates, are being produced. Dust causes harmful environmental effects.

The aim of this study was to define the extent of dust dispersion and to find out critical parameters affecting it in hard rock quarries. The most critical parameters affecting the dust concentration and dispersion appears to be the wind direction, seasonal climatic conditions, number of crushing units and capacity of the drill. In addition, the commercial software AERMOD BREEZE for dust dispersion modelling was tested to find out the usability of short-term modelling results. Dust was measured in eight aggregate quarries and in two natural stone quarries. The measurements were made inside the quarry area with a nephelometer. Performed measurements and modelling results were compared with published data.

During the production the dust concentration within aggregate quarries was a few thousand μg PM₁₀/m³. The secondary crushing generated approximately 1 700 μg PM₁₀/m³ and tertiary crushing about 3 400 μg PM₁₀/m³, measured 50 m downwind from the source. Compared to crushing, drilling produced significantly less dust: between a few tens to few hundreds of μg PM₁₀/m³.

The background concentration of PM₁₀ was reached at extrapolated distances of 750 m, 350 m, and 100 m from the tertiary crushing, secondary crushing, and drilling of natural stone, respectively. During the wintertime, the PM₁₀ concentration near the secondary crushing was approximately 1 700 μg/m³, whereas during the summertime, it was roughly 170 μg/m³.

Modelling performed well for crushing during the summertime as the modelled concentrations were same order of magnitude (93%) with the measured ones. However, modelling was unable to react sufficiently into ground inversion during wintertime and predicted concentrations of crushing were approximately 5% of the measured ones. The modelling was not able to predict reliably the hourly fluctuation of dust dispersion in the vicinity of a quarry. Modelling with on-site weather monitoring data and comparison of measured concentrations should be conducted to verify this conclusion.

Keywords Crushing, drilling, dust mass concentration, dust dispersion, PM₁₀, PM₂.₅

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Tiivistelmä

Avolohinta on merkittävä teollisuuden ala monissa maissa. Merkittäviä pölypäästöjä syntyy tuotettaessa kivianestuotteita, kuten murseita. Pöly aiheuttaa haitallisia ympäristövaikutuksia.


Pölypitoisuus kivianeslouhosilla oli noin muutama tuhat µg PM\textsubscript{10}/m\textsuperscript{3}. Kaksivaihemurskaus tuotti noin 1 700 µg PM\textsubscript{10}/m\textsuperscript{3} ja kolmivaihemurskaus noin 3 400 µg PM\textsubscript{10}/m\textsuperscript{3} mitattaessa 50 m myötätuuleen pölylähteestä. Murskaamiseen verrattuna poraus tuotti huomattavasti vähemmän pölyä: muutamasta kymmenestä muutamaan sataan µg/aan PM\textsubscript{10}/m\textsuperscript{3}.

PM\textsubscript{10}-n taustapitoisuus saavutettiin ekstrapoloiduilla etäisyyskilöillä 750 m:n, 350 m:n ja 100 m:n kolmi- ja kaksivaihemurskauksesta sekä porauksesta. Talvella PM\textsubscript{10}-pitoisuus kaksivaihemurskaamisen lähellä oli noin 1 700 µg/m\textsuperscript{3}, kun taas kesäisin se oli noin 170 µg/m\textsuperscript{3}.

Mallinnusohjelma suoritui hyvin mallinnettaessa murskauskentä pölyämistä kesääikaan, sillä mallinnetut pitoisuudet olivat samaa suuruusluokkaa (93 %) mitattujen kanssa. Mallinnus ei kuitenkaan pystynyt reagoimaan riittävästi talviaikaiseen pintainversioon ja mallinnetut murskauskentä pölypitoisuudet olivat noin 5 % mitatuista. Mallinnuksella ei pystytty luotettavasti ennustamaan pölyn leviäminen tuntivaihtelua louhoskentä läheisyydessä. Tämän päätelmän vahvistamiseksi tulisi tehdä mallinnus käytäen louhosalueen säätiloja ja verrata mallinnustuloksia mitattuihin pitoisuksiin.

Avainsanat
Murskaus, poraus, pölyn massapitoisuus, pölyn leviäminen, PM\textsubscript{10}, PM\textsubscript{2.5}

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Lemu, 22 June 2023

Marjo Hannele Sitkiä (previously Sairanen, originally Karjalahti)
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<th>Description</th>
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<td>C5</td>
<td>Model of the situation during measurements made in aggregate quarry 5</td>
</tr>
<tr>
<td>C7</td>
<td>Model of the situation during measurements made in aggregate quarry 7</td>
</tr>
<tr>
<td>CW</td>
<td>Crosswind</td>
</tr>
<tr>
<td>DW</td>
<td>Downwind</td>
</tr>
<tr>
<td>d1</td>
<td>Drill type 1. A drill which is specially modified from a forest machine to meet the needs of natural stone production.</td>
</tr>
<tr>
<td>d2</td>
<td>Drill type 2. A commercial drill.</td>
</tr>
<tr>
<td>D1</td>
<td>Model of the situation of measurements made in natural stone quarry B using the higher emission factor value determined by Aatos (2003)</td>
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<tr>
<td>D2</td>
<td>Model of the situation of measurements made in natural stone quarry B using the lower emission factor value determined by Aatos (2003)</td>
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<tr>
<td>D3</td>
<td>Model of the situation of measurements made in natural stone quarry B using the emission factor determined by US EPA (2004a)</td>
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<tr>
<td>EEA</td>
<td>European Environment Agency</td>
</tr>
<tr>
<td>EF</td>
<td>Emission factor</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>H</td>
<td>Horizontal drilling</td>
</tr>
<tr>
<td>NQW</td>
<td>Next quarry wall, i.e. on the top of the next, upper quarrying level</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
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<tr>
<td>PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Particles suspended in air which passes through a size-selective inlet with a 50% efficiency cut-off at a 10-μm aerodynamic diameter</td>
</tr>
<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;</td>
<td>Particles suspended in air which passes through a size-selective inlet with a 50% efficiency cut-off at a 2.5-μm aerodynamic diameter</td>
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<tr>
<td>PM&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Particles suspended in air which passes through a size-selective inlet with a 50% efficiency cut-off at a 1-μm aerodynamic diameter</td>
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<tr>
<td>R&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Coefficient of determination</td>
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REF WS  Reference wind speed
RH      Relative humidity
TSP     Total suspended solids
US EPA  United States Environmental Protection Agency
UW      Upwind
V       Vertical drilling
WRF     Weather Research and Forecasting
QA-QB   Natural stone quarries A and B, where dust measurements were performed during the wintertime
Q1-Q6   Aggregate quarries 1, 2, 3, 4, 5, and 6, where dust measurements were performed during the wintertime
Q7-Q8   Aggregate quarries 7 and 8, where dust measurements for modelling purposes were performed during the summertime
List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals


Author’s Contribution

**Publication 1:** A review of dust emission dispersions in rock aggregate and natural stone quarries

Marjo Sitkiä (prev. Sairanen) is the main author and coordinated the writing of the article, wrote the bulk of the text, and collected the results. The other co-authors commented on the manuscript and provided insights especially into the discussion and conclusions.

**Publication 2:** Dust emission from crushing of hard rock aggregates

Marjo Sitkiä (prev. Sairanen) is the main author. She was responsible for the study setup, made the measurements, processed the measured data, and performed the data analysis. Mikael Rinne commented on the manuscript and delivered insights, especially into the description of production. Both authors contributed to the discussion and conclusions.

**Publication 3:** Dust formed during drilling in natural stone quarries

Marjo Sitkiä (prev. Sairanen) is the main author. She was responsible for the study setup, made the measurements, processed the measured data, and performed the data analysis. Olavi Selonen was responsible for the geological descriptions of the stone material and provided comments on the paper. Both authors contributed to the discussion and conclusions.

**Publication 4:** Near field modelling of dust emissions caused by drilling and crushing

Marjo Sitkiä (prev. Sairanen) is the main author. She was responsible for the measurements and modelling with AERMOD BREEZE (a complete air quality modelling system approved by US EPA). Saku Pursio performed modelling with BRUNO (Metso Minerals’ Bruno Process Simulation software). Both authors contributed to the discussion and conclusions.
1. Introduction

Rock material is widely needed, e.g. in the construction of roads and buildings. According to the Organisation for Economic Co-operation and Development (OECD), raw material use is set to double from its 2017 level by 2060, from 90 Gigatonnes to 167 Gigatonnes. The increase comes despite a structural change and technological improvements, i.e. a shift from manufacturing to service industries and continuous improvements in manufacturing efficiency (OECD 2018a&b). Non-metallic minerals, such as sand, gravel, limestone, and crushed rock, account for more than half of the total materials consumed today in Gigatonne terms (OECD 2018b). The increase in raw material consumption is not similar for all materials. The growth of non-metallic minerals is likely to be stronger than for other material groups and they are projected to grow rapidly, from 35 Gt in 2011 to 82 Gt in 2060. Their use will grow especially rapidly in the short run, given their strong links to investment and construction needs and a lack of high-value recycling (OECD 2018a).

Recycling, compensatory materials, and the related technology have helped replace only a small part of the total consumption of rock material (European Commission 2010). Several projects aim to support more circular raw material use (e.g. OECD 2018a; European Commission 2020), which may lead to a significant increase in the usage of recycled materials in the future. Recycling will gradually become more competitive than the quarrying of minerals as a result of projected technological developments and changes in the relative prices of production inputs, but for now the relatively high labour costs for secondary production methods prevent the further penetration of secondary materials (OECD 2018a).

Open-pit quarrying constitutes a core industry in many countries and dust is a harmful environmental issue related to it. Significant fugitive dust emissions appear when different types of rock products, such as aggregates, are being produced. These emissions can cause environmental, health, safety, and operational effects that mainly affect the personnel of the quarry, but also the environment and community around the quarry. Inside the quarry, problems are generally related to labour safety and outside it to adverse environmental impacts (Almeida et al. 2002), such as hygiene problems in buildings, constructions, and vegetation (Korkmaz et al. 2011).

Dust is a generic term describing fine solid particles that are suspended in the atmosphere. According to Hinds (1999), dust is formed by the mechanical disintegration of a parent material, such as by crushing or grinding. Dust particle size is the most frequently applied categorisation property, since all the properties of a particle depend on its size, some very strongly so, such as the time of deposition. Aerodynamic diameter is a commonly applied concept when defining the size of a dust particle. The diameter refers to a spherical particle with a density of 1000 kg/m$^3$ that has the same settling velocity as the particle in question (Hinds 1999).
Total suspended particles (TSP) have a wide size range, since it includes all particles suspended into the air. TSP represent particles ranging from 0.1 μm to 100 μm (EEA 2020), while an aerodynamic diameter of 30 μm is commonly applied to represent TSP (US EPA 1995). PM generally refers to particulate matter. PM$_{10}$ and PM$_{2.5}$ are particles suspended in air which passes through a size-selective inlet with a 50% efficiency cut-off at an aerodynamic diameter of 10 μm and 2.5 μm, respectively (SFS-EN 12341 2014; SFS-EN 16450 2017). PM$_{2.5}$ or smaller particles are usually referred to as fine particles (US EPA 1995) and PM$_{10}$ or larger particles as coarse particles (Hinds 1999). PM$_{10}$ is also referred as respirable particles (Hinds 1999). The definitions of particle size categories include also the smaller particles, e.g. TSP and PM$_{10}$ both include PM$_{2.5}$. Largest particles of the size category in question compose a large proportion of the mass concentration; for example, each 10 μm particle has 1 000 times the mass of a 1-μm particle (Hinds 1999). Due to the large proportion of mass concentrating into the largest particles of the size fraction in question, approximation of TSP and PM$_{10}$ as coarse-grained dust is justifiable, though they include fine particles also.

The legislation of the EU region has determined yearly limit values for PM$_{10}$ and PM$_{2.5}$ in the air, which are 40 μg PM$_{10}$/m$^3$ and 25 μg PM$_{2.5}$/m$^3$, respectively. In Finland, national legislation determines that aggregate quarrying can take place at a distance of at least 300 m from residential areas.

The United States Environmental Protection Agency (US EPA 2004a) categorises dust emission sources in open-pit quarries into process and fugitive dust sources. Process source emissions can be captured and subsequently controlled (e.g. crushing inside a baghouse). Fugitive dust sources involve the re-entrainment of settled dust by wind or machine movement, causing the dust to arise from the mechanical disturbance of granular material exposed to the air. Emissions from process sources should be considered fugitive unless the sources are contained in an enclosure with a forced-air vent or stack (US EPA 2004a). Fugitive dust poses one of the major problems in quarries because it is generated from unconfirmed sources, such as the quarry area and transportation, and it escapes capture (Petavratzi et al. 2005).

According to US EPA (2004a), the variables affecting dust properties and behaviour are

1. material properties (including rock type, crusher feed size and distribution, and moisture content),
2. process factors (including process throughput rate, type of equipment and process practices, size reduction rate, and fines content) and
3. environmental factors (including topography and climate).

1.1 Background and research environment

Crushing and sieving produces aggregates in different particle sizes in rock aggregate quarries. The aggregates from the bedrock are extracted by drilling and blasting. The blasting aims to detach the material from the bedrock to a size that is suitable for loading and hauling and for feeding into the feeding bin of a crusher. Oversize rock blocks are fragmented with a hydraulic impact hammer or by means of drilling and blasting before crushing. Crushing usually includes several crushing phases. Jaw crushers are mainly used for primary crushing in Finnish hard rock quarries. Secondary, tertiary, and quaternary crushers are usually cone or gyratory crushers (Figure 1). An impact crusher is rarely used with hard rock materials because of wearing.
Commonly, an encapsulated sieve is adopted together with every crushing unit apart from the primary crusher.

![Figure 1. Aggregate production via crushing with two crushing units (i.e. secondary crushing). Osiris nephelometer measurement device in the foreground.](image)

All the processes of aggregate production are potential sources of dust emissions. During crushing, a jaw or a cone movement triggers rock fragmentation by inducing a compressive stress on the material in the crusher. Rock fragmentation at localised high pressure during grain-jaw/cone and grain-grain contact contributes most of the dust particles (Belardi et al. 2013). In aggregate quarries, the process that generates the most dust is crushing and sieving (Petavratzi et al. 2005; Bada et al. 2013). Drilling and blasting also cause dust emissions, but their impact is usually assumed to be insignificant compared to that of crushing and sieving (Petavratzi et al. 2005). The dust formed during the crushing is commonly controlled with encapsulation or housing and water sprays.

According to the European standard EN 12670 (2001) (Natural stone—Terminology), natural stone is defined as a piece of naturally occurring rock. Natural stone is cut out of solid rock into large solid rectangular blocks. Natural stone blocks are detached from the bedrock by drilling, smooth blasting, diamond wire sawing, or wedging. The aim is to detach stone blocks and the bedrock as intact as possible from the excavation without causing damage (Selonen & Heldal 2003). The detached primary block is subdivided into smaller blocks, which are further shaped into final sizes and dimensions, mainly by drilling and hydraulic splitting (Figure 2). The final product of the quarry is a stone block with a definite size and shape.

Drilling generates the majority of the dust formed in the processes employed in natural stone quarries (Organiscak & Page 2005; Sairanen 2014). Drilling produces dust when a drilling stem intrudes into the rock, for which reason drills are usually equipped with dry dust collection systems (Organiscak & Page 2005) in open-pit quarries. Drilling taking place in open-pit quarries applies air flushing, which does not reduce dust dispersion, while drilling taking place
Introduction

underground applies wet drilling and water flushing, which reduces the dispersion of dust into the air.

Figure 2. A natural stone block is further processed by drilling and wedging. Osiris nephelometer measurement device in the foreground.

Blasting produces a high, short-term – two to three minutes long – dust peak, which spreads over the quarry area with the prevailing wind (Abdollahisharif et al. 2016). The duration of the initial formation of a gas and dust cloud caused by blasting is measured in seconds (Khazins et al. 2020). The larger the blast, the larger the amount of dust formed (Khazins et al. 2020; Makkwao & Prueksasit 2021), which is expectable.

All quarries include the hauling of raw material and products. The quarry area itself and hauling are also significant dust sources (Reed, 2003), especially during dry and windy weather conditions. According to Reed (2003), hauling produces as much as 80–90% of the dust in open-pit quarries. Haul road dust is mainly formed during other processes in the quarry (e.g. crushing) and the hauling re-entrains the dust in the air (Kissell 2003).

All dust sources in quarries, that is, drilling (Organiscak & Page 1995; Sairanen 2014), blasting (Abdollahisharif et al., 2016), crushing (Bada et al., 2013), and hauling (Reed, 2003; Pimmonsree et al. 2009), are reported to produce mainly coarse-grained dust ($\text{PM}_{10}$ or larger). Belardi et al. (2013) observed that the aerodynamic diameters of dust particles are independent of the operating conditions of the crusher. The maximum aerodynamic diameter of the particles formed during crushing was about 70–80 μm (Belardi et al. 2013). This is in accordance with the Office of the Deputy Prime Minister (2005), stating that crushing produces mainly coarse particles (> 30 μm) and smaller particles from quarries (less than 10 μm) represent a small proportion of dust.

Besides particle size, the decrease in the dust concentration (i.e. dust retention) depends on the prevalent weather conditions. Wind speed and direction are essential. When the wind speed remains below 1 m/s, the dilution and dispersion are minimal (Aatos 2003). Smaller particles remain airborne longer, deposit more slowly, and spread over a wider area, while
larger particles deposit more quickly (Office of the Deputy Prime Minister 2005). Rainfall increases dust removal from the air and the removal is more pronounced in the case of larger particles (Hinds 1999). An increase in relative humidity (RH) has also been observed to reduce the dust concentration in the air (Chang 2004).

According to report by Office of Deputy Prime Minister (2005) large particles (> 30 µm) settle nearby, within 100 m of the dust source, and intermediate-sized particles (10–30 µm) are likely to travel up to 200–500 m. Climatic conditions, where dust – for example sand from the Sahara Desert – travels thousands of kilometres, are infrequent (i.e. not a monthly occasion) and are therefore excluded from this research.

Dust dispersion and retention can be predicted with modelling. Modelling uses mathematical equations, describing the atmosphere, the dispersion, and the physical processes within the plume, to calculate concentrations at various locations (Holmes & Morawska 2006). Modelling dust concentrations is commonly related to regulatory purposes and environmental permits. According to Venkatram et al. (2004), the dispersion models commonly used for regulatory applications generally underestimate the lower range of pollutant concentrations and overestimate the high pollutant concentrations in the near field of the dust source. The suitability of the models for particle dispersion modelling depends on the nature of the concentration desired. The factors affecting the choice of the model include e.g. the complexity of the environment, the dimensions of the model, the nature of the particle source, and the accuracy and timescale of the calculated concentrations desired (Holmes & Morawska 2006). US EPA has listed preferred models, which include e.g. the AERMOD and CALPUFF Modelling Systems (US EPA 2015).

Modelling the dust concentrations produced during open-pit quarrying has revealed that site-specific meteorological conditions and both the in-pit and surrounding terrain have a strong influence on the predicted dust dispersion (e.g. Appleton et al. 2006; Lowndes et al. 2008; Silvester et al. 2009; Tartakovsky et al. 2013). Characterisation of the dust emission source is essential because mischaracterisation of a source can impact on the modelled concentrations by an order of magnitude (Reed 2005).

The in-pit terrain causes re-circulatory airflows, which create microclimates within the quarry. It is evaluated that between 30 and 70% of the fugitive dust emissions from quarrying activities remain within the quarry boundary (e.g. Reed 2005; Lowndes et al. 2008; Silvester et al. 2009). The location of the dust source in relation to the quarry walls and wind direction have been noticed to have an effect on dust dispersion (e.g. Appleton et al. 2006; Lowndes et al. 2008; Torno et al. 2011).

### 1.2 Research Problem

Dust measurements are commonly conducted for regulatory purposes to ensure adequately controlled exposure of dust (Petavratzi et al. 2005). Exposure takes place e.g. via breathing and settling on a surface. Previous studies have reported highly varying results of dust produced from quarrying: PM\textsubscript{10} concentrations measured within a quarry area vary between 40 µg/m\textsuperscript{3} (Almeida et al. 2002) and 210×10\textsuperscript{3} µg/m\textsuperscript{3} (Madungwe & Mukonzvi 2012). The current knowledge was gathered in Publication 1, to form the basis of further research.

Dust measurements in real operating conditions are demanding because of the large number of variables affecting the spreading of the dust. Critical parameters in dust measurements in
open-pit quarries include the sampling location, the time of the measurement, and climatic factors such as wind speed and direction, temperature, and moisture (Petavratzi et al. 2005). In addition, important factors in dust measurements include the sampling duration, sampling and analytical end methods (e.g. weighing), data handling and analysis, and supplementary data collection (UK Environment Agency 2000). According to the Office of the Deputy Prime Minister (2005), the majority of the particles formed in quarries (i.e. particles > 30 µm) will deposit within 100 m from the source. However, Cattle et al. (2012) observed in dust deposition measurements that dust spreads several kilometres away from quarries. Therefore, measurements with a similar study setup in different open-pit quarries were performed in order to better understand dust emissions, variations in concentration, and decreases in dust concentrations with increasing distance (Publications 2 and 3).

Modelling and measurements have been compared in some studies (e.g. Sivacoumar et al. 2009; Tartakovsky et al. 2013&2016), but none of them deals with the behaviour of dust dispersion at short distances, a hundred metres or less, and during short time periods such as hours. Complaints of dust from a quarry spreading into the neighbourhood appear near quarries, mainly within a few hundred metres, and concern certain days or even a time of the day. Therefore, the usually modelled situation of yearly concentration averages does not represent well the situation experienced in the nearby residential areas. Modelling the dust dispersion and comparing predicted concentrations into measured ones was performed (Publication 4).

1.3 Aim of this study

Quarrying commonly requires environmental permits. The permit process demands detailed information on the harmful environmental effects caused by quarrying in order to ensure the acceptability of a planned quarry. This study aims to define the extent of dust dispersion i.e. at what distance the dust is still measurable with the equipment used, and separable from background. Another aim is to find out the critical parameters for dust emissions. A further aim is to assess if a commercial dust dispersion model is applicable to model short-term dust dispersion near the quarry area, where the closest residential areas may appear. The focus is to gain information of dust concentration and dispersion for evaluating environmental effects of open-pit quarrying. The results are intended to be utilized for the assessment of the environmental impacts of quarrying operations.

Health effects of dust are excluded from this study.

The research problems presented in the previous subchapter resulted in the following research questions, which are answered in this dissertation:

I. Does the previous research provide generalisable results for dust emissions (e.g. similar concentration levels) caused by quarrying activities?

II. Do measurements with the same study setup in different quarries provide dust concentration levels formed during crushing or drilling applicable to other quarries operating with similar equipment?

III. How far does the dust propagate from the quarrying activities (i.e. crushing and drilling)?

IV. Is a commercial modelling program able to predict short-term dust dispersion near the dust source (and to be used to steer production to prevent harmful environmental effects)?
This dissertation is structured as follows:

Chapter 2:  *Research methodology*
A summary of the methods used in this research.

Chapter 3:  *Dust concentrations caused by crushing and drilling*
Dust concentrations caused by crushing and drilling observed in previous studies and measured in this research. The results of measurements performed in this research apply to mobile crushers and drills used in natural stone quarrying. Answers are given to Research Questions I (Publication 1) and II (Publications 2 and 3).

Chapter 4:  *Dust retention*
The decrease in dust concentration with increasing distance (i.e. dust retention) is determined both for previous studies and measurements made in this research for crushing and drilling. The results are applicable to mobile secondary crushers and drills used in natural stone quarrying and give an answer to Research Question III (Publications 2 and 3).

Chapter 5:  *Modelling of dust dispersion*
Evaluating the usability of a commercial modelling program when considering the vicinity of the quarry area. The modelled results are compared with the measured ones and Research Question IV (Publication 4) is answered.

Chapter 6:  *Conclusions and recommendations.*
2. Research methodology

The methods employed in the individual publications included gathering the current knowledge to form a state-of-the-art review of dust produced during quarrying, measuring dust concentrations in different quarries, and modelling quarry dust dispersion and comparing it to measured concentrations. This chapter provides a brief summary of the research methods and more detailed descriptions are presented in the respective publications.

First, a state-of-the-art review of current knowledge was formed to provide a systematic overview of the dust concentrations caused by open-pit quarrying (Publication 1). This literature study was based on research mainly found from Elsevier and SpringerLink peer-reviewed journals. The analysis in Publication 1 was restricted to open-pit quarries and mines operating in open pits with similar production phases: drilling, blasting, hydraulic impact hammering, crushing, and sieving. The focus was on environmental effects and fugitive dust near or inside open-pit quarries. Health-related studies were excluded. A total of 25 studies were reviewed in Publication 1.

The dust measurements were conducted in aggregate and natural stone quarries (Publications 2 and 3). The measurements were made inside the quarry area with Turnkey Osiris nephelometer (see Figure 3). The process producing the most dust, crushing and drilling, was measured during wintertime, when other dust sources were absent or minimal because of the snow cover on the ground. Measurements were conducted at six aggregate quarries and two natural stone quarries in Finland. The aggregate and natural stone quarries included in this research represent the largest aggregate and natural stone producers in Finland. Measurements were made under real operating conditions and all measurements employed the same study setup, thus providing to some extent comparable results. The quarry area and walls, as well as the location of production equipment (crusher or drill), together with the wind direction, set limitations on the sampling locations. All the measured mobile crushers had two, three, or four crushing units, involving primary, secondary, tertiary, and quaternary crushing stages. Therefore, the effects of a specific crushing unit are not analysed in this study.

The dust concentrations measured and modelled in this research were all average mass concentrations (from now on concentrations). The concentrations observed in the previous studies (Publication 1) and measurements made in this study (Publications 2, 3, and 4) are reported in Chapter 3. Utilising all measurements made for this research, the effect of weather conditions on dust concentration are discussed in Chapter 3. Data from national weather stations was utilised when evaluating the effects of weather conditions on dust concentrations.

Dust retention was also studied, and how far the dust propagates from the dust source was evaluated (Publications 2 and 3). Dust retention in previous studies (Publication 1) and in this study (Publications 2 and 3) is presented in Chapter 4.
Finally, dust dispersion from quarries was modelled (Publication 4). A commercial model AERMOD BREEZE was chosen in order to evaluate the model’s performance and applicability, since it is accepted to be used for particle dispersion modelling by US EPA. The modelling was performed using the data and circumstances of the actual quarries where dust measurements were conducted. The modelled results were compared with the measured ones. A comparison was made for two previously measured quarries (one aggregate and one natural stone quarry) and two additional aggregate quarries, which were measured for modelling purposes (Publication 4). The modelling is covered in Chapter 5.

Publication 1 gathers the knowledge of the previous research. Publications 2 and 3 provide dust concentration results from several quarries measured with the same study setup and therefore provide a broader perspective on dust formation during quarrying compared to case studies concentrating on one site. Publication 4 implies that there are restrictions of modelling short-term dust concentrations in the vicinity of a quarry area.

Figure 3. The nephelometer operating principle (modified from Turnkey Instruments Ltd 2014) [Publication 3].
3. Dust concentrations caused by crushing and drilling

The formation and spreading of dust during open-pit quarrying are insufficiently studied environmental issues. Studies with the same setup at several sites are needed to gain generalisable information on dust concentrations caused by quarrying processes. Similar study setups were utilised in Publications 2 and 3 to measure several quarries and crushers and drills and in Publication 4, when measuring two quarries for modelling purposes.

This chapter summarises the findings of previous research (Publication 1) and the results achieved in this study (Publications 2, 3, and 4).

3.1 Review of previous studies

Publication 1 focused on environmental effects and fugitive dust near or inside open-pit quarries. The dust measurements covered the quarry area and/or the ambient environment or measurements concentrated on certain quarrying processes, e.g. drilling.

The results were divided according to the main dust-producing quarrying processes, among which crushing, and drilling are included here. Fifteen studies covered crushing and nine drilling. Dust was measured with several different measuring techniques and set-ups.

The dust concentration results near crushing, i.e. 50 m or less or within the quarry boundary, varied significantly between the studies. For coarse particles (TSP and PM10) the results varied between 80 and 37 000 µg TSP/m³ and from 110 to 36 000 µg PM10/m³. For fine particles (PM2.5), the range of results was from 50 to 1 200 µg PM2.5/m³.

The variation was even higher when considering coarse dust produced during drilling. The results varied from 95 to 95 000 µg TSP/m³ and from 60 to 16 000 µg PM10/m³. The variation of fine particles was modest, from 10 to 70 µg PM2.5/m³.

As shown above, review of previous studies revealed a wide dust concentration range for crushing and drilling: Some concentrations were really high and some really low, but most of the results were between these extremes. Upper values can be used for conservative evaluations of dust emissions caused by a planned quarry. However, a risk of an overestimation of coarse particles is probable.
3.2 Dust measurements

Since the previous research reports highly variable results on dust emissions and dispersion from quarries, and since measurements under real operating conditions according to the same study setup are not frequently made in several quarries, measurements in several quarries with similar measuring setups are needed to gain more knowledge of dust and dust dispersion near quarry areas to evaluate their effects better.

Dust dispersion was measured in aggregate and natural stone quarries. Measurements were made under real operating conditions (see Figure 4) and with similar measuring setups. No adjustments were made to aggregate or natural stone production on account of the dust measurements.

The aggregate and natural stone quarries included in this research represent the largest aggregate and natural stone producers in Finland. The equipment used in quarrying activities is commonly used in Finland and widely employed in Europe also. All the aggregate quarries are located in granite or gneiss formations (Table 1), except aggregate quarry 3, which mainly processed limestone. Both natural stone quarries are located in hard rock formations.

The aggregate quarries included in this research utilised mobile crushers applying two, three, or four crushing units: secondary, tertiary, and quaternary crushing, respectively. The mobile crusher operates typically as a one whole unit, for example, tertiary crushing includes primary and secondary crushing also, and therefore, primary crushing with one crushing unit is not discussed in this research. The natural stone quarries used both vertical and horizontal drilling.

All the quarries that were studied were open pits. In aggregate quarries the activity that produces the most dust is assumed to be crushing and in natural stone quarries it is assumed to be drilling. As stated in previous research studies (e.g. Reed 2003; Chang et al. 2010), hauling is also a significant source of dust. Nevertheless, hauling was excluded from the measurements since the majority of the measurements were conducted during wintertime and the resuspension of dust from haul roads was minimal because of the snow cover on the ground. In Table 1 the quarries included in this research are presented.
Table 1. Ten quarries where dust emissions were measured [Publications 2, 3, and 4].

<table>
<thead>
<tr>
<th>Quarry ID and quarry type</th>
<th>Dust source</th>
<th>Production capacity</th>
<th>Products</th>
<th>Stone material processed</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1: Aggregate quarry*</td>
<td>Secondary crusher: two units</td>
<td>200 t/h</td>
<td>Aggregates: 0-32 mm</td>
<td>Granodiorite</td>
<td>2</td>
</tr>
<tr>
<td>Q2: Aggregate quarry*</td>
<td>Tertiary crusher: three units</td>
<td>170-200 t/h</td>
<td>Aggregates: 0-11 mm and 0-32 mm</td>
<td>Mica gneiss</td>
<td>2</td>
</tr>
<tr>
<td>Q3: Aggregate quarry*</td>
<td>Secondary crusher: two units</td>
<td>400-450 t/h</td>
<td>Aggregates: 0-32 mm</td>
<td>Limestone, gneiss, amphibolite</td>
<td>2</td>
</tr>
<tr>
<td>Q4: Aggregate quarry*</td>
<td>Secondary crusher: two units</td>
<td>400 t/h</td>
<td>Aggregates: 0-90 mm</td>
<td>Mica gneiss</td>
<td>2</td>
</tr>
<tr>
<td>Q5: Aggregate quarry*</td>
<td>Secondary crusher: two units</td>
<td>200 t/h</td>
<td>Aggregates: 0-32 mm</td>
<td>Microcline granite, pyroxene gneiss</td>
<td>2 and 4</td>
</tr>
<tr>
<td>Q6: Aggregate quarry*</td>
<td>Quaternary crusher: four units</td>
<td>250-300 t/h</td>
<td>Aggregates: 0-8 mm and 8-16 mm</td>
<td>Mica gneiss</td>
<td>2</td>
</tr>
<tr>
<td>Q7: Aggregate quarry**</td>
<td>Quaternary crusher: four units</td>
<td>200 t/h</td>
<td>Aggregates: 0-4 mm, 0-45 mm, 4-11 mm, 11-16 mm</td>
<td>Microcline granite</td>
<td>4</td>
</tr>
<tr>
<td>Q8: Aggregate quarry**</td>
<td>Tertiary crusher: three units</td>
<td>200 t/h</td>
<td>Aggregates: 0-16 mm and 0-32 mm</td>
<td>Migmatite</td>
<td>4</td>
</tr>
<tr>
<td>QA: Natural stone quarry*</td>
<td>Drill</td>
<td>50 m/h and 80 m/h</td>
<td>Stone blocks</td>
<td>Rapakivi granite</td>
<td>3</td>
</tr>
<tr>
<td>QB: Natural stone quarry*</td>
<td>Drill</td>
<td>50 m/h</td>
<td>Stone blocks</td>
<td>Rapakivi granite</td>
<td>3 and 4</td>
</tr>
</tbody>
</table>

* Measurements were made during the winter
** Measurements were made during the summer for modelling purposes

All the crushers were mobile and had a partial encapsulation of conveyors and crushing units already installed in the manufacturing plant. No dust prevention techniques, such as watering, were applied during the measurements due to risk of freezing while crushing in Quarries 1–6. When measuring in Quarries 7 and 8, watering was paused during the measurements in order to gain results under similar production conditions to those measured earlier in Quarries 1–6 during the wintertime.

Figure 4. Mobile crusher, drill, and hydraulic impact hammer in an aggregate quarry. Osiris nephelometer measurement device in the foreground.
Dust concentrations caused by crushing and drilling

There were two drill types employed in the natural stone quarries during the study: drill types 1 and 2. Drill type 1 (d1) was specially modified from a forest machine to meet the needs of natural stone production (Figure 5). Drill type 2 (d2) was a commercial drill with a higher drilling capacity compared to d1 (Figure 6). Drilling was conducted in both horizontal (H) and vertical (V) directions (Figures 5 and 6). All the drills were equipped with dust control systems which functioned properly during the measurements.

Figure 5. Horizontal drilling with a drill modified from a forest machine (d1H) in natural stone Quarry B. Dust measurement in the downwind (DW) and crosswind (CW) directions at distances of 5 m and 10 m, respectively [Publication 3]. Osiris nephelometer measurement device shown in the foreground and on the right.

Figure 6. Vertical drilling with a commercial drill (d2V) in natural stone Quarry A [Publication 3].
Measurements were conducted with two Turnkey Osiris nephelometers (see Figure 5). Four sets of particle sizes were measured simultaneously: TSP, PM$_{10}$, PM$_{2.5}$, and PM$_{1}$. When measuring all sizes at the same time, the maximum capacity of the nephelometer is approximately 6 000 μg/m$^3$. The Turnkey Osiris nephelometer is standardised for PM$_{10}$ fractions of up to 100 μg/m$^3$ (Turnkey Instruments Ltd, 2009&2014). Light scatter technology has been observed to perform adequately, compared to gravimetric measurement devices, when measuring dust formed in a basalt quarry (Degan et al. 2013) and in a coal terminal (Ecowise Environmental 2007). The performance of Osiris was comparable to a gravimetric reference method measuring PM$_{10}$ from ambient air in Finland (Waldén et al. 2010; Waldén & Vestenius 2018). Therefore, the Osiris nephelometer is applicable, since quarrying produces mainly coarse (PM$_{10}$ or larger) particles.

Average dust mass concentrations (from now on dust concentrations) were measured at different distances in the downwind (DW), upwind (UW), and crosswind (CW) directions (Figure 7). The distances of measurements varied between 5 and 200 metres and was dependent on quarry properties. The measurements were mainly conducted at the same elevation as the dust source. In aggregate Quaries 7 and 8 measurements were also conducted at the top of the next quarry wall. These measurements were made during active daytime quarry operations.

The measurements of background concentration (i.e. particle concentration in the air without the particles formed during the quarrying processes) were made during the nighttime.

The dust concentration measurements revealed the expected result that the concentrations were in general highest at the DW measurement locations and lowest at the UW measurement locations. The dust concentrations measured at the CW locations were in a range between the results measured at the DW and UW locations. Some incoherent results were obtained as a result of local dust sources, such as for hauling in the natural stone Quarry A and in the aggregate Quarry 3.

Dust concentrations were similar for coarse (TSP and PM$_{10}$) and fine particles (PM$_{2.5}$ and PM$_{1}$) and therefore, the results for PM$_{10}$ and PM$_{2.5}$ are used to represent coarse and fine particles, respectively. PM$_{10}$ and PM$_{2.5}$ have limit values in several countries’ legislation (e.g. in the EU region and in the USA), which is another reason to focus on these size fractions.
3.3 Dust concentrations caused by crushing and drilling

Dust concentration levels at a distance of 50 m or less from the dust source in the DW direction (DW50) varied between 165 and 6,500 µg PM$_{10}$/m$^3$ for crushing and 7 and 763 µg PM$_{10}$/m$^3$ for drilling. The variation in the case of fine particles (PM$_{2.5}$) was from 18 to 510 µg PM$_{2.5}$/m$^3$ for crushing and between 3 and 62 µg PM$_{2.5}$/m$^3$ for drilling.

Both crushing and drilling capacities influenced the dust concentration. The higher the capacity or the higher the number of process phases, the higher the dust concentration measured, which is expected.

An increase in the number of crushing units leads to a decrease in the particle size of aggregates and it also increases the timespan in which the rock material is within the process. Therefore, it increases the dust emissions from the crushing. Tertiary crushing produced roughly twice the amount of dust particles (3,400 µg PM$_{10}$/m$^3$) compared to secondary crushing (1,700 µg PM$_{10}$/m$^3$), when measured from DW50.

The dust emissions caused by drilling showed a directly proportional relationship to drilling capacity: doubling the capacity also doubled the dust concentration from 360 µg PM$_{10}$/m$^3$ to 760 µg PM$_{10}$/m$^3$, when measured from DW5.

In the limestone quarry (Quarry 3), the measured dust concentrations were approximately 50% of the concentrations measured at other quarries processing granitic rock material with similar mobile crushers producing a same-sized aggregate. The maximum capacity of a Turnkey Osiris nephelometer is approximately 6,000 µg/m$^3$. The percentage of measurements exceeding the capacity of the nephelometer was around 10% for the secondary crushing of granitic rock, whereas the crushing of limestone produced less than 5% of results exceeding the capacity of the nephelometer.

The dust concentrations near crushing measured in this study is presented in Figure 8 with observations by other researchers. The dust source concentrations associated with drilling are presented in Figure 9.

![Figure 8. PM$_{10}$ concentrations during crushing in aggregate quarries in the downwind (DW) direction at a distance of 50 m or less. Quarries 1, 4, and 5: secondary crushing of granitic rock material. Quarry 3: secondary crushing of limestone. Quarries 2 and 6: tertiary and quaternary crushing of granitic rock material, respectively. Quarry 7: tertiary crushing of granitic rock material, measurements made during the summer.](image-url)
As is shown in Figure 8, the lowest dust concentrations were measured while processing limestone with secondary crushing (Publication 2) and during the tertiary crushing of granitic rock material in the summer (Publication 4). Dust concentrations of the same order of magnitude were observed during the processing of limestone by Almeida (2002) and of granite by Bada et al. (2013). Dust concentration levels during crushing in Finland in the 2000s showed significantly lower results compared to measurements obtained in the 1990s (Junttila et al. 1996&1997).

Dust formation during the drilling in the studies by Golbabaei et al. (2004), Olusegun et al. (2009), and Degan et al. (2013) is mainly higher compared to the results reported by Sairanen (2014) and concentrations measured in this study (see Figure 9). The highest and the lowest dust formation during the drilling was measured by Olusegun et al. (2009) and Bada et al. (2013), respectively.

3.4 Size distribution and background concentration

The percentages of all the measured size fractions in relation to TSP concentrations are presented in Table 2.

<table>
<thead>
<tr>
<th>Quarry type</th>
<th>TSP (%)</th>
<th>PM$_{10}$ (%)</th>
<th>PM$_{2.5}$ (%)</th>
<th>PM$_{1}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarry: crushing</td>
<td>100</td>
<td>60</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Natural stone quarry: drilling</td>
<td>100</td>
<td>67</td>
<td>17</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 9. PM$_{10}$ concentrations during drilling in natural stone quarries in the downwind (DW) direction at a distance of 50 m or less.
As percentages of Table 2 show, crushing and drilling produces mainly (50% or more) coarse particles, especially crushing. Open-pit quarrying has also previously been reported to contribute mainly into coarse particles than fines (e.g. Gautam et al. 2015; Sahu et al. 2018). In the literature study, TSP concentrations were approximately two to four times greater than the concentration of PM\(_{10}\). Tartakovsky et al. (2016) estimated that TSP is approximately two times the concentration of PM\(_{10}\) and fine particles (PM\(_{2.5}\)) approximately 7% of TSP. These are in accordance with the findings made in this study, since the TSP concentration was approximately 1.7 times the concentration of PM\(_{10}\) for crushing and 1.5 times for drilling (see Table 2).

Background concentrations were mainly low, reflecting the concentrations measured in rural areas in Finland (Hiukkastieto 2014). Natural stone quarries are mostly located in remote rural areas, whereas aggregate quarries are located within a few tens of kilometres from cities. The background concentrations measured in the quarries are presented in Table 3.

<table>
<thead>
<tr>
<th>Quarry type</th>
<th>TSP (µg/m(^3))</th>
<th>PM(_{10}) (µg/m(^3))</th>
<th>PM(_{2.5}) (µg/m(^3))</th>
<th>PM(_{1}) (µg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarry</td>
<td>30</td>
<td>16</td>
<td>3.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Natural stone quarry</td>
<td>11</td>
<td>8.5</td>
<td>4.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### 3.5 Variation in concentrations during quarrying activities

The typical variation in concentrations during quarrying activities was significant, varying between 1 and 6,500 µg/m\(^3\) and from 1 to more than 650 µg/m\(^3\) for coarse and fine particles, respectively (Publications 2 and 3). The measured concentration was for the most part clearly lower than the peak concentrations (see Figures 10 and 11). The peak concentrations were several times higher compared to the general lower level and even same as the measurement capacity of the nephelometer or higher. This is also supported by statistical analysis; the median concentrations were lower compared to the average concentrations. The average concentrations of coarse particles were approximately two to six times the median concentrations for crushing and approximately two to five times for drilling. The average concentrations of fine particles were approximately one to two times the median concentration for both crushing and drilling.

When considering the environmental effects of dust, the average concentration was assumed to be more representative compared to the median values, which were lower compared to the average concentrations. Using the average concentrations avoids underestimation when evaluating the environmental effects of dust.
Dust concentrations caused by crushing and drilling

Figure 10. An example of PM$_{10}$ concentration during crushing in an aggregate quarry in the downwind (DW) direction. Grey line: concentration at a constant distance of 30 m from the crusher. Black line: concentration at distances of 50 m, 75 m, 100 m, and 125 m from the crusher. The maximum measured concentration was $6.5 \times 10^3$ µg/m$^3$, which exceeds the measurement capacity of the nephelometer [Publication 2].
Dust concentrations caused by crushing and drilling

Figure 11. An example of PM$_{10}$ concentration during drilling in a natural stone quarry in the downwind (DW) direction. Grey line: concentration at a constant distance of 5 m from the drill. Black line: concentration at distances of 10 m, 20 m, and 30 m from the drill. The maximum measured concentration was $6.5 \times 10^3$ µg/m$^3$, which exceeds the measurement capacity of the nephelometer [Compiled from measurements reported in Publication 3].

As Figures 10 and 11 show, both crushing and drilling have a significant effect on dust concentrations in the DW direction. The concentration drops within a minute when crushing or drilling is stopped. During a break in production, PM$_{10}$ levels were 2% compared to the concentration measured during crushing or drilling. During the break, PM$_{2.5}$ levels were 3% and 6%, compared to the concentration during the crushing and drilling, respectively.

The concentration during the break in crushing was approximately twice the background concentration for aggregate production. Also, the concentration of PM$_{10}$ during the break in drilling in a natural stone quarry was approximately twice the background concentration, whereas the concentration of PM$_{2.5}$ during the break in a natural stone quarry was approximately the same as the background concentration.

3.6 Concentration levels compared to literature

Dust concentration results near the crushing (i.e. 50 m or less from the crusher, or within the quarry boundary) in the reviewed previous studies varied significantly, but the majority of the results were a few thousand µg PM$_{10}$/m$^3$. This is in the same order of magnitude, as the concentrations measured near the crusher in this research. As mentioned in chapter 3.3., tertiary
crushing generated about twice the amount of PM$_{10}$ compared to secondary crushing, when measured from DW50. Makkwao and Prueksasit (2021) observed that tertiary crushing produced nearly five times the PM$_{10}$ concentration compared to secondary crushing. Degan et al. (2013) measured a concentration that was over 20% higher for secondary crushing (approximately 5 400 µg PM$_{10}$/m$^3$) compared to primary crushing (approximately 4 400 µg PM$_{10}$/m$^3$), while Saramak et al. (2022) observed more than twice the concentration of secondary crushing (3 400 µg PM$_{10}$/m$^3$) compared to primary crushing (1 200 µg PM$_{10}$/m$^3$).

Fine particle concentrations near the crusher were mainly between 100 and 400 µg PM$_{2.5}$/m$^3$ both in the previous and in this study. According to percentages of measured PM$_{2.5}$ of TSP gained in this research, proportion of fine particles is low (under 10 % of TSP). Since crushing applies heavy machinery and combustion engines are a source of fine particles, it is assumed, that fine particles originate mainly from the machinery and other, remote sources rather than crushing process itself.

According to the literature study, the variation in the coarse dust produced during the drilling was high: between 60 and 16 000 µg PM$_{10}$/m$^3$. In this research, the dust concentration at 50 m or less from the drill in the DW direction varied between a few tens and a few hundred µg PM$_{10}$/m$^3$. Thus, the measured dust concentrations resulting from drilling were significantly lower than the figures found in the literature for coarse particles. All the drills measured in this study were equipped with a dust collector, which is the main reason for the lower coarse particle concentrations compared to previous findings.

The results of the fine particle concentrations measured during the drilling were similar both in the previous studies and this one. In both, the concentrations were from approximately ten to a few tens of µg PM$_{2.5}$/m$^3$. Fine particles are assumed to originate mainly from other sources (e.g. combustion engines, remote sources) than the drilling process itself, since these low concentrations were of the same order of magnitude both in this and in the previous studies. Also, the percentages of measured PM$_{2.5}$ of TSP, proportion of fine particles is rather low (under 20 % of TSP).

The crushing of limestone seemed to produce less dust compared to the crushing of granitic rock material. In the limestone quarry (Quarry 3), the measured dust concentrations were approximately 50% of the concentrations measured at other quarries processing granitic rock material with similar mobile crushers producing a same-sized aggregate. This lower concentration level for coarse particles (mainly a few hundred µg/m$^3$) near the crusher in limestone quarries was also observed in some previous studies (Almeida et al. 2002; Chang 2004; Bluvshtein et al. 2011). This may be explained by the mineral texture. Granitic rocks are hard but brittle and limestone (dolomite) is tough and their crushability may differ (Comakli & Cayirli 2019). Hence limestone may produce fewer dust particles when broken into smaller pieces in the crushing process. Another factor leading to lower dust concentrations may be that limestone requires a shorter crushing time than granite (Olaleye 2010). This difference between the dust concentrations observed in limestone quarries and quarries processing granitic rock material is incompatible with the conclusion drawn by EPA (2004b), stating that the rock type is not a major variable for dust emissions in aggregate quarries.

A differing result compared to the observation of low dust emissions caused by limestone quarrying made in this study was recently reported from a limestone mine in Thailand by Makkwao and Prueksasit (2021). They measured PM$_{10}$ concentrations caused by secondary and tertiary crushing as being 1 000–17 000 and 11 000–74 000 µg/m$^3$, respectively. These recent measurements were made inside the crushing circuit, as were the measurements made
Dust concentrations caused by crushing and drilling

by Junttila et al. (1996&1997), who also reported concentrations of tens of thousands of µg/m³. Both of these high concentrations observed by Makkwao and Prueksasit (2021) and Junttila et al. (1996&1997) are probably due to the measurements being made inside a crushing circuit (i.e. right next to the crushing unit). Other research measurements, both those included in the literature review of Publication 1 and the measurements made in this research, were made outside the crushing circuit.

3.7 Effects of weather conditions on measured concentrations

All the weather parameters that were considered – temperature, relative humidity, and wind speed – showed partly unsystematic effect on the measured dust concentrations in the DW direction. The results were similar for all size categories. For the most part, the weather conditions lacked a notable effect on the measured concentrations.

The weather conditions stayed relatively constant during the measurements made during the winter in each quarry, 1–6. Slightly different weather conditions appeared during the measurements in the different quarries. This complicates the comparability and ability to observe the impacts of weather conditions. Since the variation in the weather conditions was modest, only indicative changes were observed.

Temperature mainly had no effect on dust concentrations, and an increase in temperature was observed to either increase or decrease the measured dust concentration. An increase in wind speed (WS) and relative humidity (RH) indicated a decrease in the dust concentration in the air. An increase in WS leads to more efficient mixing i.e. the dust spreads into a larger volume of air. An increase in RH contributes to coagulation, where the large absorbing surface of the dust particle causes smaller water droplets diffusion to that surface (Hinds 1999), resulting the formation of larger particles, which remain airborne for a shorter time and settle faster. This coagulation between dust particles and water droplets occurs in seconds. The mass of water droplets is significantly smaller compared to the dust particle mass and therefore, the impact of RH on the dust mass concentration remains uncertain. With the mass concentrations observed in this study, the coagulation between dust particles is slow due to low number concentration and this coagulation occurs mainly slower than timeframe used in this study.

During the wintertime, the PM₁₀ concentration resulting from the secondary crushing was approximately 1700 µg/m³, whereas during the summertime, it was roughly 170 µg/m³ at a distance of 50 m from the crusher. This is due to ground inversion occurring during the winter. During wintertime, ground inversion is typical and then conditions are stable, which prevents the particles from mixing into large air masses. During ground inversion, the air is cooled by contact with the colder surface of the earth until it becomes cooler than the atmosphere above it, which prevents air flows from near the surface into the upper overlying atmosphere. Instead, in the summer the mixing is more efficient, because the sun produces enough heat to erode the inversion. Most likely, the measured concentrations were lower during the summertime compared to the wintertime as a result of the diluting effect of the more efficient mixing of dust particles into larger air masses.

Similar concentration behaviour was observed in Greece by Samara et al. (2018), who found out that mean seasonal concentrations of PM₁₀ were relatively higher (1.3–1.5 times) in the cold period (November–December) compared to the warm period (August–September).
Kumar et al. (2017) also gained similar effects, reporting a higher concentration of air pollutants during the winter season.
4. Dust retention

Determining the environmental effects of dust from quarries is challenging because of several environmental variables, such as topography, wind, and moisture content. According to previous studies, the dust produced during quarrying consists of coarse particles, which settle near the dust source, the majority of them within 100 m of it (Office of the Deputy Prime Minister 2005). However, some studies suggest that the dust particles are spread several kilometres away from the quarries (e.g. Cattle et al. 2012). An overview is given of dust retention determined in previous studies (Publication 1) and the measurements reported in Publications 2 and 3.

4.1 Dust retention in previous studies

Dust concentration decrease evaluations for crushing were possible in three studies and for drilling in two, among 25 studies reviewed (Publication 1). These studies addressed dust retention of coarse particles. For both crushing and drilling, only one research study covered dust retention of fine particles and therefore it is considered only briefly.

Chang (2004) and Olusegun et al. (2009) reported a decrease in dust concentrations with increasing distance from the crusher, but according to Sivacoumar et al. (2006), dust concentrations showed no systematic reduction with increasing distance. Their evaluation included results from all the measuring stations around an aggregate quarry. When the analysis of the concentrations measured by Sivacoumar et al. (2006) is restricted to a certain compass point (approximately east), the decrease in the dust mass concentration with increasing distance becomes more pronounced (Figure 12).
The evaluation of the distance needed for achieving the background concentration varied in the studies that were reviewed from 30 m (Reed 2003) to 9 000 m (Cattle et al. 2012). A significant decrease in the PM$_{10}$ concentration was observed within a few tens of metres from crushing: at a 25 m distance the dust concentration from crushing was less than 50% of the concentration measured at the source (Olusegun et al. 2009). According to the results gained by Sivacoumar et al. (2006), the background concentrations are achieved at distances of 1 210 and 990 m for PM$_{10}$ and PM$_{2.5}$, respectively. The results presented in Figure 12 imply that the decrease in dust concentration with increasing distance observed by Chang (2004) is in between the dust retention perceived by Sivacoumar et al. (2006) and Olusegun et al. (2009).

The dust concentration decreases significantly within a few tens of metres from the drilling in a natural stone quarry (Figure 13).
Olusegun et al. (2009) observed the PM$_{10}$ concentration as being roughly 25% at a distance of 25 m from the drill compared to the concentration measured at the source. A concentration decrease with increasing distance is also observed with longer distances and with low concentration levels (Aatos 2003), but the decrease is more pronounced in the immediate surroundings of the drill. Larger-size fractions decrease faster compared to smaller ones: the background concentrations are achieved at distances of 55 and 80 m for coarse (PM$_{10}$) and fine (PM$_{2.5}$) particles, respectively (Sairanen 2014).

4.2 Concentration decreases with increasing distance

Dust concentration decreases rapidly with increasing distance with all wind directions and all size categories (TSP, PM$_{10}$, PM$_{2.5}$, and PM$_{1}$). As expected, the decrease is the most pronounced in the UW direction. However, exceptions were observed for all wind directions due to other quarrying activities (especially hauling) affecting results.

The decrease in the DW direction is slower compared to the CW and UW directions; hence retention in the DW direction is important for assessing how far the dust may propagate from the quarry. Figures 14 and 15 present the decrease in the mass concentration in the DW direction with increasing distance for coarse (PM$_{10}$) and fine (PM$_{2.5}$) particles, respectively.
Dust retention

Figure 14. Dust retention of coarse particles (PM$_{10}$) from crushing and drilling in the downwind (DW) direction from the dust source. Crushing first y-axis and drilling second one [Compiled from Publications 2 and 3].

Figure 15. Dust retention of fine particles (PM$_{2.5}$) from crushing and drilling in the downwind (DW) direction from the dust source. Crushing first y-axis and drilling second one [Compiled from Publications 2 and 3].

Figures 14 and 15 present dust retention from secondary crushing in aggregate Quarry 5 and from horizontal drilling in natural stone Quarry B. Both occurred in isolated locations and in the absence of other dust sources (see also Figures 16 and 18). They both had the lowest (about
10%) variation in results. The number of measurement locations in the DW direction was highest in Quarries 5 and B among the crushers and drills that were measured.

As Figures 14 and 15 show, the retention was more pronounced in the immediate surroundings (within a few tens of metres) from the dust source. This is due to the absence of other interfering dust sources between the dust source and the measuring station.

Dust retention to distance was extrapolated via the best fitting curve with MS Excel. Exponential dust retention curves were adopted because of the higher coefficient of determination ($R^2$) compared to the linear retention. An exponential function has also been applied to dust retention modelling (e.g. Reed 2005). The exponential dust retention formulae are given for secondary crushing in aggregate Quarry 5 (equations 1-4 from Publication 2) and for horizontal drilling in natural stone Quarry B (equations 5-8 from Publication 3):

\begin{align*}
\text{crusher} C_{\text{TSP}} &= 5248.6 \times e^{-0.0019X} \\
\text{crusher} C_{\text{PM10}} &= 5106.9 \times e^{-0.024X} \\
\text{crusher} C_{\text{PM2.5}} &= 203.99 \times e^{-0.016X} \\
\text{crusher} C_{\text{PM1}} &= 47.93 \times e^{-0.021X} \\
\text{drill} C_{\text{TSP}} &= 235.9 \times e^{-0.034X} \\
\text{drill} C_{\text{PM10}} &= 172.0 \times e^{-0.037X} \\
\text{drill} C_{\text{PM2.5}} &= 20.18 \times e^{-0.02X} \\
\text{drill} C_{\text{PM1}} &= 3.99 \times e^{-0.022X}
\end{align*}

where $C_{\text{TSP}}$, $C_{\text{PM10}}$, $C_{\text{PM2.5}}$, and $C_{\text{PM1}}$ are the concentrations in $\mu g/m^3$ of TSP, PM$_{10}$, PM$_{2.5}$, and PM$_1$, respectively. $X$ is the distance from the crusher or the drill in metres. These equations are applicable when processing hard rock material with mobile crushers and drills equipped with dust collector, having capacities approximately 200 t/h and 50 m/h, respectively.

The distance was extrapolated for the DW direction from the source to the point where the background dust concentration is achieved. These distances for each measured particle size categories are presented in Table 4.

### Table 4. Extrapolated distance in a downwind direction, where the background concentration is achieved for all measured size categories (TSP, PM$_{10}$, PM$_{2.5}$, and PM$_1$) [Publications 2 and 3].

<table>
<thead>
<tr>
<th>Quarry</th>
<th>TSP Distance (m)</th>
<th>PM$_{10}$ Distance (m)</th>
<th>PM$_{2.5}$ Distance (m)</th>
<th>PM$_1$ Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarries:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarry 1</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Quarry 2</td>
<td>777*</td>
<td>743*</td>
<td>211*</td>
<td>101*</td>
</tr>
<tr>
<td>Quarry 3</td>
<td>347</td>
<td>308</td>
<td>270</td>
<td>312</td>
</tr>
<tr>
<td>Quarry 4</td>
<td>364</td>
<td>341</td>
<td>N.R.R.</td>
<td>N.R.R.</td>
</tr>
<tr>
<td>Quarry 5</td>
<td>267</td>
<td>234</td>
<td>286</td>
<td>209</td>
</tr>
<tr>
<td>Quarry 6</td>
<td>717*</td>
<td>695*</td>
<td>373*</td>
<td>221*</td>
</tr>
<tr>
<td>Natural stone quarries:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarry A</td>
<td>74</td>
<td>69</td>
<td>61</td>
<td>55</td>
</tr>
<tr>
<td>Quarry B</td>
<td>90</td>
<td>83</td>
<td>102</td>
<td>105</td>
</tr>
</tbody>
</table>

N.A. = Not available, less than three measurement locations.

N.R.R. = No reliable results available because of anomalies in measurement.

* Tentative result: More than 5% of the samples exceeded the capacity of the measurement device.
The background concentration was reached at an extrapolated distance of approximately 350 m from secondary crushing and 100 m from drilling (see Table 4). The results suggest that dust formed in quarries employing tertiary crushing spread to a wider area compared to secondary crushing and the background concentration is achieved at a distance of roughly 750 m. The retention results for tertiary crushing are indicative, because more than 5% of the DW measurements exceeded the nephelometer’s capacity. From analytical point of view, the background concentration is never reached, but these approximations are applicable when evaluating environmental effects of quarrying dust.

The yearly limit values of PM$_{10}$ and PM$_{2.5}$, set both in the national and EU legislation, are 40 µg PM$_{10}$/m$^3$ and 25 µg PM$_{2.5}$/m$^3$, respectively. The limit values of PM$_{10}$ and PM$_{2.5}$ are reached at distances of 200 m and 100 m, respectively, for secondary crushing, and at distances of 40 m and 10 m, respectively, for drilling.

The limit values are already reached inside the quarry area during the drilling, but not during the crushing. The national legislation defines that the nearest residential areas and other sensitive objects must be located at least 300 m from aggregate quarries. According to the results gained in this study, aggregate quarrying employing secondary crushing does not exceed the limit values for particulate matter in residential areas. When the current distance limitation of 300 m continues to be valid, dust measurements in residential areas do not provide reliable results of the dust formed during quarrying, because it does not cause reliably separable concentrations at such distances. The dust measurements beyond 300 m from the quarry area are more indicative of activities in the surroundings of the quarry, such as agriculture and traffic.

The background concentrations measured in this study were low in general since the concentration levels represent rural areas in Finland (Hiukkastieto 2014). The background concentration depends on the time of the measurements. During the night, the dust concentration is lower because of the lack of dust sources, such as traffic. Low background concentrations are a consequence of the time of the measurements, which were made during the night. The background concentration measurements during the night allowed results to be gained during similar seasonal climatic conditions and locations as when measuring the dust from the quarrying process. Breaks in the quarrying production lasting several days appear usually only during the summer in Finland, mainly in July but also in June and August. The impact of the seasonal weather conditions of winter and summer is greater than the impact of the background concentration measurement occurring at non-dusty times of the day.
5. Modelling of dust dispersion

Dust dispersion modelling is commonly related to regulatory purposes and environmental permits. Modelling can provide an essential tool when evaluating the effects of a planned quarry. The model performance was evaluated within the quarry boundary, less than 200 m from the dust source, during a period lasting from three to five hours. This time window is important, as short-term dust dispersion events are the main cause of complaints in the vicinity of a quarry. If the model can capture the short-term variation in the dust dispersion, it could be used to evaluate the circumstances during which dust prevention should be enhanced or production even paused.

The modelled dust dispersions are compared with the measured concentrations close to the source (200 m or closer) to evaluate the performance of the model within the quarry area. The comparison was made in a natural stone quarry and in two aggregate quarries (Publication 4). In the natural stone quarry, the dust source was drilling and in the aggregate quarries, it was crushing.

5.1 Modelled quarries

The results from the models of a natural stone quarry and two aggregate quarries are compared with the measured dust concentrations near the dust sources. The results that had the most measurement locations in a DW direction were selected to be modelled. These were crushing in aggregate Quarry 5 (Publication 2) and natural stone Quarry B with horizontal drilling (Publication 3). Additional measurements were made in aggregate Quarries 7 and 8 (Publication 4). The wind direction in the quarry area in Quarry 8 differed from the wind direction observed at the nearest national weather station, causing the modelled dust plume to travel in the opposite direction compared to the measurement locations. This resulted in zero predicted concentrations at the measurement locations, and Quarry 8 is therefore omitted from further consideration.

5.2 Applied modelling program and emission factors

The dust dispersion modelling software that was used was BREEZE AERMOD, version 8.0.0.39 (from now on AERMOD). AERMOD was the chosen model used in this study, since it is accepted for modelling particle dispersion by environmental authorities (e.g. US EPA 2018). Furthermore, AERMOD has been previously reported to perform adequately while modelling
dust emissions from open-pit quarries (e.g. Sivacoum et al. 2009; Tartakovsky et al. 2013 & 2016) and it has been reported to provide reliable near-field concentration estimates (e.g. Venkatram et al. 2004; Demirarslan et al. 2017).

Emission factor (EF) is a coefficient that describes the rate at which a certain activity releases a certain pollutant into the atmosphere. Since US EPA (2004a) has determined the EFs for various phases of quarrying and they are commonly applied, e.g. when modelling dust dispersion for regulatory purposes, they were used in this study. US EPA (2004a) defines the EF only for wet drilling. Since the natural stone Quarry B used dry drilling, the EF for dry drilling determined by Aatos (2003) was also used in the modelling. The lower and upper ends of the EF range for dry drilling were applied.

Quarrying produces mainly coarse (PM$_{10}$ or larger) particles and EFs are more widely available for PM$_{10}$ than for TSP. Therefore, the modelling was performed for the size fraction PM$_{10}$. PM$_{10}$ also has limit values in legislation, e.g. in the U.S. and the EU region.

AERMOD uses the EFs in the form of g/s, which was also applied by Aatos (2003). US EPA (2004a) determines the EFs in the form of kg/t of processed rock. The number of production phases and announced capacities of the measured drill and crushers were used when transforming the EF into the unit demanded by AERMOD. The detailed information used in the calculation of the EFs and the EFs used in the modelling are presented in Table 5.

Table 5. Modelled cases and respective emission factors (EFs) [Publication 4].

<table>
<thead>
<tr>
<th>Modelling case ID</th>
<th>Dust source</th>
<th>Production capacity of drill/crusher</th>
<th>Dust source to which EF is given</th>
<th>Emission factor (kg PM$_{10}$/t)</th>
<th>Emission factor (g PM$_{10}$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5</td>
<td>Secondary crushing in aggregate Quarry 5</td>
<td>200 t/h</td>
<td>Crusher, Sieve, Conveyor transfer point in total</td>
<td>0.0012** 0.0043** 0.00055**</td>
<td>0.0667 0.23889 0.06112 0.36671</td>
</tr>
<tr>
<td>C7</td>
<td>Tertiary crushing in aggregate Quarry 7</td>
<td>200 t/h</td>
<td>Crusher, Sieve, Conveyor transfer point in total</td>
<td>0.0012** 4×0.0043** 4×0.00055**</td>
<td>0.0667 4×0.23889 4×0.06112 1.26674</td>
</tr>
<tr>
<td>D1</td>
<td>Horizontal drilling in natural stone Quarry B</td>
<td>50 m/h*</td>
<td>Dry drilling</td>
<td>-</td>
<td>0.504***</td>
</tr>
<tr>
<td>D2</td>
<td>Horizontal drilling in natural stone Quarry B</td>
<td>50 m/h*</td>
<td>Dry drilling</td>
<td>-</td>
<td>0.213***</td>
</tr>
<tr>
<td>D3</td>
<td>Horizontal drilling in natural stone Quarry B</td>
<td>50 m/h*</td>
<td>Wet drilling</td>
<td>4 × 10**</td>
<td>0.001549</td>
</tr>
</tbody>
</table>

The EFs input are presented in bold

* Stone block drilled during the measurements: 25 m × 8 m × 6 m, distance between drill holes 0.3 m
** US EPA (2004a)
*** Aatos (2003)

5.3 Topography and meteorological parameters

The topography of all the quarries that were studied is characterised by a large flat area bordered by steep quarry walls. In the natural stone quarry, this topography is the most pronounced since the height difference between the flat quarry bottom and the top of the quarry walls was approximately 30 m, whereas in the aggregate quarries (Quarry 5 and 7) the elevation difference was approximately 10 m.
The national coordinate systems and elevations were used in the model to create a 3D surface in AERMOD. The surface model was built via receptor points, which created the flat area at the bottom of the quarry and steep quarry walls. The receptor points were also located in the same spots as the site dust measurements for all the quarries that were modelled.

Data from the nearest national weather stations was applied. They located approximately 15 km to the south, 40 km to the south, and 45 km to the south-east from the Quarry 5, 7, and B, respectively. The meteorological data was purchased from the BREEZE Software company, and it needed no additional processing before being entered into the modelling program.

The meteorological data of the actual date and hours of the day when the site dust measurements took place was used in the modelling. The measurements and therefore also the models covered three- to five-hour periods. Modelling is usually applied for longer time periods, e.g. months or even years.

### 5.4 Comparison of measured and modelled concentrations

The hourly averages of the modelled PM$_{10}$ results were compared to the hourly averages of the measured concentrations. The comparison was made with reference points, in other words the receptor points entered into the model, which corresponded to the actual measurement locations in the quarry. The focus was on dust retention in the DW direction.

The modelled concentrations in Quarry 5 suggest about 5% of the measured concentrations, while the modelled dust concentration for crushing in Quarry 7 suggests approximately 93% of the measured concentrations. Figures 16 and 17 present the modelled concentration contours and the measured results in Quarries 5 and 7, respectively. The dust measurements were made in the observed DW direction and the distance from the crusher is given in metres.
Figure 16. Dust dispersion of PM$_{10}$ in the downwind (DW) direction from the secondary crusher in Quarry 5. Modelled concentration contours 10 (green), 50 (yellow), and 100 (orange) µg/m$^3$. The measured concentrations are given for each measurement location (X). Aerial photograph: Google Earth Pro [Publication 4].
The modelled results of drilling using the EF from Aatos (2003) are 20 to 50 times higher compared to the measured concentrations. When using the EF from US EPA (2004a), the modelled results are approximately $16 \times 10^{-3} \%$ of the measured concentrations. Figure 18 presents the modelled concentration contours for drilling of the model D2 (a lower EF from Aatos [2003] was applied) and the measured dust concentrations during measurement day 1. The dust measurements were made in the observed DW direction and the distance from the drill is given in metres.
5.5 Site-specific emission factors

Since all the EFs previously determined by Aatos (2003) and US EPA (2004a) resulted in low correlation between the modelled and measured concentrations, site-specific EFs were determined. The site-specific EFs were calculated using the average ratios of the difference between the modelled and measured concentrations (equation 9):

\[
\text{EF}_{\text{site-specific}} = \text{EF} \times \frac{C_{\text{measured}}}{C_{\text{modelled}}}
\]

where \(\text{EF}_{\text{site-specific}}\) and \(\text{EF}\) are the site-specific emission factor and the emission factor from the literature, respectively. \(C_{\text{measured}}\) and \(C_{\text{modelled}}\) are the measured and modelled concentrations in the same sampling location, respectively.

For secondary crushing in the aggregate Quarry 5, the difference between the modelled and measured concentrations leads to a site-specific EF of 8.15 g/s. For quaternary crushing in the aggregate Quarry 7, the difference between the modelled and measured concentrations leads to a site-specific EF of 1.36 g/s. These site-specific EFs are in contradiction of the EFs of US EPA (2004a), see Table 5, and previous observations that an increase in the number of crushing stages increases the amount of dust produced during the crushing (e.g. Petavratzi et al.)
2007). This contrary result in site-specific EFs is a consequence of seasonal climatic conditions (i.e. inversion). Nevertheless, these site-specific EFs are of the same order of magnitude as the EF determined by Chakraborty et al. (2002): on average 4.7 g/s for a mine overall.

For drilling, the ratios gained from all three modelled cases (D1, D2 and D3) led to a site-specific EF of 0.005 g/s for drilling, while EF of US EPA (2004a) was 0.0015 g/s. This US EPA (2004a) EF for wet drilling underestimated the concentration. The underestimation in this case is expected, since the natural stone quarry B employed dry drilling, which is expected to produce more dust compared to drilling with water flushing. Chakraborty et al. (2002) determined the EF for drilling to be 0.34 g/s, which is nearly 70 times greater compared to the site-specific EF for drilling determined in this study. The variable EFs gained in different studies and differences in EFs for modelling provided by the respected organisations the European Environment Agency (EEA) and US EPA (Ghannam & El-Fadel 2013) show that determining EFs still needs more research.

5.6 Dust retention: Measured vs. predicted

Exponential dust retention curves for PM$_{10}$ were determined from the measurements for all the modelled quarries. The previously determined background concentration of PM$_{10}$ 16 µg/m$^3$ (Publication 2) was applied for the aggregate Quarry 7 in Publication 4. For Quarry 7, the measured background concentration is achieved at a distance of approximately 340 m.

The distance at which the background concentration is reached for the modelled concentrations is also given (Publication 4). An exponential dust decay curve was determined according to the modelled concentrations at the reference points (i.e. measurement locations). Dust decay curves were determined for both previously defined and site-specific EFs. Both the measured and modelled distances for the background concentrations of PM$_{10}$ are presented in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Assessed from measurements (m)</th>
<th>Assessed from predicted concentrations modelled with EF from US EPA (2004a) for crushing (m) and Aatos (2003)/US EPA (2004a) for drilling (m)</th>
<th>Assessed from predicted concentrations modelled with site-specific EF determined in Publication 4 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing, C5</td>
<td>234*</td>
<td>118</td>
<td>292</td>
</tr>
<tr>
<td>Crushing, C7</td>
<td>338</td>
<td>130</td>
<td>124</td>
</tr>
<tr>
<td>Drilling, D1/D2/D3</td>
<td>83**</td>
<td>93/80/10</td>
<td>26</td>
</tr>
</tbody>
</table>

* Publication 2  
** Publication 3

Modelling results in faster dust retention compared to the measurements, except in the aggregate Quarry 5, where the modelled results (C5) using the site-specific EF predict slightly slower dust retention compared to the measurements (Table 6). The site-specific EFs did not result notable improvement on more aligned dust retention results with measured ones compared to EFs of US EPA.
5.7 Usability of the short-term nearfield modelling

The performance of the model was evaluated via quantile-quantile plots (Q-Q plots) and calculating statistical key figures. The Q-Q plots for crushing and drilling are presented in Figure 19. Because all the modelled drilling situations behaved alike, the results of the model D2 in relation to the measurements are presented in Figure 19.

![Figure 19. Comparison of the modelled and measured PM_{10} concentrations for both crushing and drilling. Models C5 and C7 represent crushing in the aggregate Quarries 5 and 7, respectively. Model D2 represents drilling in natural stone Quarry B. Emission factors of crushing according to US EPA (2004a) and drilling according to Aatos (2003) [Compiled from Publication 4].](image)

The measured and modelled concentrations did not align well in this study. This is also supported by statistical key figures, which showed no statistically significant correlation between the measured and modelled results. The coefficient of determination ($R^2$) was 0.52 and 0.15 for crushing in Quarries 5 and 7, respectively. For drilling, $R^2$ was 0.24 for all the modelled EFs. None of the modelled situations shows statistical significance in relation to the measurements, but the modelled situation C5 for crushing in aggregate Quarry 5 can be considered indicative.

The comparison between the measured and the modelled dust concentrations showed that the AERMOD model is more sensitive to changes in the weather conditions than the measurements, which showed no significant changes during the measurements made for this research. The model’s sensitivity to changes in weather conditions was also noted by Tartakovsky et al. (2013).

Evaluation of the usability of the model revealed that AERMOD is not able to model the dust concentration fluctuation inside the quarry area and its near vicinity when using the weather data from the national weather stations. AERMOD is previously reported to have better performance compared to other available modelling programs when modelling dust from
quarrying (e.g. Tartakovsky et al. 2013&2016). Nevertheless, AERMOD was not able to predict the hourly concentration fluctuation in the time span examined. The main reason for this is assumed to be the lack of on-site meteorological data. The climatic conditions in the open pits were unlikely to be precisely the same as those measured by the national weather station located several kilometres away. The shorter the distance between the sources and the meteorological stations, the higher the chances are that the topographical barriers will not affect the wind field and interfere with dispersion predictions (Tartakovsky et al. 2016). Especially in complex terrain, on-site meteorological data is seen as being crucial (Tartakovsky et al. 2013). The remote location of the weather stations is assumed to be the main reason for the low performance of the model.

Besides the lack of on-site weather parameters, low performance of the model in relation to the measured results is affected by the steady state assumption of AERMOD, which prevents the model from responding to temporal and spatial variations in the meteorological conditions (Stovern et al. 2014). Because of this steady state assumption, the model is not fully capable of modelling the air flows within the quarry area and near its boundaries (e.g. Lowndes et al. 2008; Silvester et al. 2009; Haq et al. 2019). The in-pit air flows cause dust emissions to remain within the quarry boundary (e.g. Lowndes et al. 2008) and the escape rate (i.e. the proportion of dust escaping from the quarry with air flows) decreases rapidly as the diameter of the particle size increases: the escape ratios are 71%, 67%, 19%, and 0% for PM$_{2.5}$, PM$_{10}$, PM$_{30}$, and PM$_{50}$, respectively (Wanjun & Qingxiang 2018).

The most significant difference between the measured and modelled concentrations was a consequence of seasonal climatic conditions and this seasonal effect led to the contrary result in site-specific EFs. Modelling with AERMOD and using the EF determined by US EPA for crushing predicted well the dust dispersion near the dust source during the summer, but the model was unable to predict the high dust concentration during the wintertime. This, it is suggested, is a consequence of ground inversion and more stable climatic conditions during the winter compared to the summer. This caused a significant underestimation of the modelled dust concentrations for the winter season since ground inversion trapped dust particles so that they remained near the ground and apparently the modelling does not take this phenomenon sufficiently into account.
6. Conclusions and recommendations

The aim of this thesis was to define the extent of dust dispersion and to find out critical parameters affecting it in hard rock quarries. A further aim of this study was to evaluate if a commercial dust dispersion model is applicable when modelling short-term dust dispersion in the quarry area. The results are intended to be utilized for the assessment of the environmental impacts of quarrying operations. The conclusions are based on a literature review, field measurements, and modelling results.

The outcomes of the literature review presented in Publication 1 are in line with the measurements made for this thesis: crushing generates more dust compared to drilling and quarrying activities produce mainly coarse particles (TSP and PM\(_{10}\)) which settle near the dust source. Fine particles (PM\(_{2.5}\)) originate mainly from other remote sources and from the machinery used in the quarries.

The dust concentration results of the previous studies that were reviewed varied significantly, but the majority of the results were a few thousand µg PM\(_{10}\)/m\(^3\), which is the same order of magnitude as observed in this study. When measuring 50 m in a downwind (DW) direction from the crushing, the secondary crushing (crushing with two crushing units) generated approximately 1 700 µg PM\(_{10}\)/m\(^3\) and tertiary crushing (crushing with three crushing units) about twice the amount: 3 400 µg PM\(_{10}\)/m\(^3\). These results are applicable for tentative approximations when processing hard rock material with mobile crushers.

The crushing of limestone produced approximately 50% of the concentrations measured at quarries processing granitic rock material. Based on the literature and this study, the research results on limestone are not consistent. Some authorities have reported that processed rock material would not affect dust emissions. Whether the rock type being processed significantly affects dust concentrations needs further research.

The dust concentration at 50 m or less from the drill in the DW direction varied between a few tens and a few hundred µg PM\(_{10}\)/m\(^3\). The highest results observed in this study were of the same order of magnitude as the lowest ones found in the literature. This is due to a dust collector being used in all the drills measured in this research and therefore, the results apply for dry drilling using a dust collector.

The background concentration of coarse particles is extrapolated to be reached at distances of 750 m, 350 m, and 100 m from the tertiary crushing, secondary crushing, and drilling of natural stone, respectively. These results are applicable for evaluating the environmental effects, when processing hard rock material with mobile crushers and drills, having capacities between 200-400 t/h and 50-80 m/h, respectively. The result for tertiary crushing is indicative because of the large proportion (> 5%) of results exceeding the measurement capacity of the nephelometer.
Seasonal climatic conditions have a crucial impact on dust concentration levels: There was a significant difference in the concentration levels between the winter and summertime measurements. During the wintertime, the PM$_{10}$ concentration near the secondary crushing was approximately 1700 µg/m$^3$, whereas during the summertime, it was roughly 170 µg/m$^3$. Apart from this seasonal variation, the measurements did not reveal separable changes according to the weather parameters (temperature, relative humidity, and wind speed), since the weather conditions stayed relatively constant during the measurements and therefore, there were no measurable changes in concentration. Further research is needed in which longer sampling periods are applied to detect the impact of varying weather conditions and to ensure the effect of wintertime and stable ground inversion conditions.

According to this research, the most critical parameters affecting the dust concentration and dispersion were wind direction, seasonal climatic conditions, and the number of crushing units or the capacity of the drill.

The AERMOD BREEZE modelling program performed well when modelling crushing during the summertime: the modelled concentrations are of the same order of magnitude (93%) as the measured ones. However, the model was unable to react sufficiently to the ground inversion during the wintertime and the predicted concentrations of crushing were approximately 5% of the measured ones. According to this study, AERMOD reproduces well the dust dispersion in aggregate quarries during unstable (non-inversion) meteorological conditions. The usage of on-site weather parameters is recommended.

The emission factors (EFs) determined for drilling by Aatos (2003) overestimated and the EF of US EPA (2004a) underestimated the dust concentration compared to the measured ones. The EF of US EPA is defined for wet drilling, so underestimation is expected. The EF of dry drilling needs further research to obtain more realistic modelling results to reflect the measured concentrations better.

The modelling was not able to predict reliably the hourly fluctuation of dust dispersion in the vicinity of a quarry in this study. According to these results, it seems that modelling is not applicable as a tool for steering production in open-pit quarries, when using data from National weather stations. Modelling with on-site weather monitoring data and comparison of measured concentrations should be conducted to verify this conclusion.
References


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