Efficacy of water suppression method for controlling the emissions of submicron particles at a quarry, Boksburg, South Africa.

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

RESEARCH REPORT

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Executive summary

Background: Respiratory diseases has contributed 70% to worldwide occupational disease mortality in all industrial sectors since over a decade ago. Pneumoconioses occur as a result of accumulation of dust in the lungs. Silicosis, one of the most common forms of pneumoconioses, presents in three different forms namely acute, accelerated, and chronic silicosis. Quarrying and open cast mining are responsible for different workplace hazards including noise, trauma, vibration, ultraviolet radiation, and dust exposure, which may cause silicosis. Lung deposition of particulate matter depend on the particulate matter surface characteristics, aerodynamic size, and weight. Quarrying and stone crushing activities are associated with high levels of crystalline silica release. Water suppression has been proven to effectively control dust in mining and construction industries, but not enough attention has been paid on effects of water suppression on fine particulate matter.

Purpose: To evaluate efficacy of water suppression as a dust control measure for submicron particles for the primary, secondary and tertiary treatment processes during the production of stone aggregates in a quarry.

Methods: In this cross-sectional study data was collected using a Nanozen dust sampling device to monitor dust emissions in 0.300µm to 10.658µm bin sizes across 4 different sampling points namely primary, secondary, tertiary treatment area, and office complex at a quarry in Boksburg, South Africa. In the primary treatment area big rocks are crushed into 150mm smaller rock without dust suppression, the secondary area breaks them further into 57mm stones with water supperssion applied, and tertiary breaks them into 19mm and smaller stone products under further water suppression conditions. Primary treatment area and office complex were sampled as dry areas, while secondary and tertiary treatment areas were sampled as water suppression areas. Data was analysed based on mass and number concentrations for different bin sizes, and comparisons were made between dry and wet areas. The effect of water treatment (suppression) on submicron bin ranges (0.300-0.915µm) in terms of mass concentration and number concentration was analysed to determine its efficacy in reducing dust emissions in this range.

Results: The total average mass concentration of 460.2 µg/m^3 (±486.3) was emitted from the primary area without dust suppression with average of 2.22E+08 (±136958.7) number concentration. This was reduced to 6.02µg/m^3 and 60.9 million (±552879) mass and number concentration respectively in secondary treatment area with water suppression. In tertiary area emissions were 10.52µg/m^3 and 54.8 million particles/cm^3 (±828126) respectively for mass and number concentrations following further water suppression, while in office area (no water suppression) 6.07µg/m^3 and 44.4 million/cm^3 mass and number concentrations were recorded respectively.

Conclusions & Recommendations: Data showed reduction of emissions between primary and secondary area by 98.7% (mass concentration) and 72.5% (number concentration). Further treatment in tertiary treatment showed a further decrease in total average number concentration compared to secondary treatment. Emissions at the office block as a control site were consistent with emissions from secondary and tertiary treatment areas, demonstrating possible dispersion by wind. Water suppression was demonstrated to be effective against particle bin sizes larger than 1 micron, with progressively less effect on submicron particles as they became smaller. More research is recommended on suppression of submicron dust particulate matter emission and consideration of number concentration as a key dose matrix to determine exposure.

Keywords: *water suppression, particulate matter, submicron particles, quarrying, silicosis.*

Declaration

The work contained in this thesis is my own, unless otherwise acknowledged. This thesis has not been presented for examination at any other university.

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2023-06-10

Dedication

To my wife and life partner Matshediso, for holding my hand and never leaving my side, and for bringing colour and meaning to my life.

To my daughters Lehakwe, Letlotlo, & Leruo, for everything you have and continue to teach me about life, and for inspiring everything I do.

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Glossary of Terms

Particulate matter: Microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems.

Fine particulate matter: Particulate matter contains microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems. Fine particulate matter refers to particles that are smaller than 2.5 microns in diameter.

Submicron particles: The portion of particulate matter that is less than 1 µm in diameter.

Ultrafine particles: The portion of particulate matter that is smaller than 0.3 microns (300nm) in diameter.

Total Suspended Particulates: Comprises all airborne or suspended particles in different bin sizes, mass concentration, and number concentration.

Interstitial lung disease: A large group of disorders which cause progressive scarring of lung tissue. They are irreversible and characterised by the scarring that may eventually affect ability to breathe and get enough oxygen into the bloodstream.

Pneumoconioses: A group of lung diseases caused by the lung's reaction inhaling certain dusts. The main cause of the pneumoconioses is work-place exposure. The three common type of pneumoconioses are asbestosis, silicosis, and coal worker’s pneumoconiosis.

Silicosis: A chronic lung disease caused by inhaling large amounts of crystalline silica dust, usually over many years. This can present as acute, accelerated, and chronic silicosis based on the duration of exposure and latency period.

Silicotuberculosis: The type of tuberculosis that occurs in patients that have already been exposed to or diagnosed with silicosis.

Opencast mine: The type of surface mining that extracts minerals from an open pit in the ground. This does require extractive methods or tunnels that are used in underground mining.

Quarrying: The process of extracting rock, sand, gravel or other minerals from the ground to be used for the production of materials for construction or other products.

Deposition: The process by which dust particles are laid down on the ground after emission from the source. This may occur immediately following emission or after transportation by wind.

Resuspension: The process by which deposited dust or particulate matter are reintroduced into the atmosphere after being physically agitated or lifted up by air.

Water suppression method: The Method of dust suppression where water is used to bind dust particles in order to render them larger and heavier and unable to move as a result. Is often the primary dust control method employed at quarries and road haulage environments.

Abbreviations and Acronyms

Aids	–	Acquired immunodeficiency syndrome
COPD	–	Chronic obstructive pulmonary disease
CVS	–	Cardiovascular system
CWP	–	Coal workers pneumonitis
FPM	–	Fine particulate matter
HIV	–	Human immunodeficiency virus
ILO	–	International Labour Organization
LEV	–	Local exhaust ventilation
LoD	–	Level of Detection
MHSA	–	Mine Health and Safety Act
PM	–	Particulate matter
PMF	–	Progressive massive fibrosis
RCS	–	Respirable crystalline silica
SIMRAC	–	The Safety in Mines Research Advisory Committee
TB	–	Tuberculosis
TSP	–	Total suspended particles
UFP	–	Ultrafine particles
WHO	–	World Health Organization
WSM	–	Water suppression method

1. CHAPTER ONE

This chapter begins with the background on the respiratory occupational diseases and their impact on human health and breaks them down according to their classification and aetiology. The chapter further outlines pneumoconiosis, its different types, and how it is diagnosed using universal and standardized approaches. The role of occupational health as a proposed solution to workplace health problems is also outlined. The problem statement and justification of study are also outlined in this chapter. The chapter ends with aims and objectives of the study. Every chapter description gives insights on what to be expected.

1.1 Background

Work-related respiratory diseases have constituted approximately 60% of all disease and injury mortality since over a decade ago and 70% of occupational disease mortality worldwide in all industrial sectors [1]. Occupational lung disease is classified into two groups namely interstitial lung diseases and airways diseases [2]. Interstitial lung disease affects the lung parenchymal tissue while airways disease, as the name suggests, affects the airways from the trachea to the alveoli [3]. Respiratory organs serve as major gateway for entry of chemicals and pathogens into the body through inhalation as a route of entry. This exposure route renders workers vulnerable to respiratory hazards [4] and also serves as the key area of focus for prevention and protection against the exposure.

Occupational airway disease encompasses restrictive and obstructive diseases, and both may result from exposure to irritants and pathogens such as tuberculosis. Common examples are occupational bronchitis, reactive airway dysfunction syndrome, bronchiolitis obliterans, and occupational asthma [5]. Interstitial lung disease includes pneumoconiosis such as asbestosis, byssinosis, chronic beryllium disease, coal workers pneumoconiosis (CWP), silicosis, flock workers' lung, and farmers lung disease [1].

Pneumoconioses are diseases that occur as a result of the accumulation of dust in the lungs [2]. This results from inhalation of the offending chemicals that are contained in the dust, leading to chronic inflammation and ultimately fibrosis. The International Labour Organization (ILO) has classified pneumoconioses according to appearance on chest radiographs and describes them in terms of features such as diffuse lung opacities and pleural disease [6]. This has helped to introduce a standard approach and interpretation of radiological features of Pneumoconioses, making them easier and more universal to diagnose. The incidence of pneumoconiosis had increased by 66% from 36186 cases in 1990 to 60055 globally in 2017 [7,8]. Silicosis, CWP, and asbestosis combined account for the majority of the fibrogenic pneumoconiosis. Silicosis and CWP alone were also the two most prevalent Pneumoconioses amongst young people between the age of 24-44 in Hubei Province, China in 2019 [9].

Occupational health programs are designed to be the effective solution to these types of problems worldwide and continue to evolve in order to be able to address emerging problems. World Health Organization defines occupational health as the area of work in public health to promote and maintain highest degree of physical, mental, and social-being of workers in all occupations [10]. The following objectives have been laid out as fundamental principles for an effective occupational health program:

1. The maintenance and promotion of workers' health and working capacity.
2. The improvement of working conditions and the working environment to become conducive to safety and health.
3. The development of work organization and working cultures that should reflect essential value systems, personnel policy, principles for participation, and voluntary quality-related management practices to improve occupational safety and health [11].

The science and practice of occupational health involve several disciplines, such as occupational medicine, nursing, ergonomics, psychology, hygiene, safety, and others [12]. The involvement of these different disciplines helps to provide a holistic and multidisciplinary approach to solving occupational health issues comprehensively [13]. Unfortunately, occupational health programs can also be very costly for employers due to legislative requirements that are set out by the governmental authorities [14].

Since the adoption of the Occupational Health and Safety guidelines in South Africa in early 1950s [15], a lot of emphasis has been focused on ensuring healthy workers and safe workplaces, and continuous improvements are made to prevent and minimize the impact of occupational hazards on employees. South Africa has taken major strides in ensuring that occupational health takes priority in the country. These include the development of legislation and regulations specific to the mining sector. The Mine Health and Safety Act (MHSA) is one of the major advancements that the country has established to implement and regulate health and safety in the mining sector. The development of comprehensive handbook on occupational health and safety in mining by The Safety in Mines Research Advisory Committee (SIMRAC) was also one of the key ingredients that ensured achievements of occupational health and safety goals in South Africa [16].

It is evident that the country has adequate legislative and operational framework to ensure health and safety in the mining industry, but however, continuous technological advancements are needed to redefine hazard identification, risk assessment, and risk management in the mining environment.

1.2 Problem statement

Mining activities are the major source of the release of dust particles in different sizes and chemical composition. The emission of particulate matter leads to poor ambient air quality. Poor outdoor and indoor air quality has led to over 7 million premature deaths globally. The International Labour Organization has reported that over 2.2 million deaths are caused by occupational diseases, translating to one employee dying each and every 15 seconds daily [17]. The toxicity of particulate matter is influenced by particle diameter, chemical composition, and internal dose. To date several dose matrices are used to estimate the emission concentration at various workplaces. However, the most common dose matrix is often expressed as mass concentration. The use of mass concentration is unfortunately suggested to be more reliable for particles in the larger size range. In order to reduce the emissions of dust particles, water suppression method is commonly the most preferred technology. The Water Suppression Method (WSM) has been proven to effectively control emissions of larger particulate matter (PM_{10}) in mining and construction industries. These particles are however not the culprits commonly associated with development of respiratory disease when compared to smaller particulate matter ($PM_{2.5}$, PM_1), and this implies that water suppression as a method may not be an effective means of preventing and controlling emission of submicron particles.

1.3 Research Question

What is the efficacy of water suppression in the reduction of emission of submicron (PM_1) particles?

1.4 Study Aim

The aim of this study was to evaluate efficacy of water suppression as a dust control measure for submicron particles for the primary, secondary, and tertiary treatment processes during the production of stone aggregates in a quarry.

1.5 Study objectives

- To monitor the mass and number concentrations of particulate matter (PM) emitted during the production of stone aggregates in the absence of water suppression.

- To monitor the mass and number concentrations of particulate matter emitted during the production of stone aggregates during water suppression.
- To monitor the mass and number concentrations of PM emitted during the production of stone aggregates during alternative wet treatment (water bath).
- To compare the concentration of PM emissions between wet and dry processes.
- To evaluate the efficacy of water suppression on submicron particle range.

1.6 Justification of the study

Water suppression is one of the oldest and most cost-effective methods for controlling fugitive dust. It does so by increasing the diameter and weight of particles, making them less likely to float in the air. Fitz et al. (2000) demonstrated the effectiveness of water against PM_{10} under windy conditions. Watering was proven effective against PM_{10} at wind speeds up to 18 metres per second (m/s). Zhang also reported that Coal Seam infusion was developed and widely applied in European coal mines for dust control. However, he challenged its viability in underground mines: "Water infusion provides effective dust mitigation measure in some coal seams. Due to presence of other more effective methods water infusion is not considered as a viable method in underground mines" [19]. In a 2015 comparative interventional study designed to demonstrate effectiveness of water suppression alone against combination with Local Exhaust Ventilation (LEV) by Cooper, cutting artificial stone countertops with wetted blade plus LEV reduced mean respirable dust and quartz exposure by factor of 10 compared to wet blade only situation [20]. This also demonstrated that water alone as a dust suppression method is inadequate in some instances.

In a South African study in 2015, du Plessis demonstrated that adding lignosulphonate to water suppression mixture as opposed to water alone reduced application frequency by 50% and water use by 50.2% in a haulage dust road environment. Dust fallout was reduced by 53.8%. This also clearly demonstrated that water alone was not very effective due to quick evaporation as also concluded by Lee in 2019. The study concluded that water suppression provides short-term effectiveness due to evaporation and requires frequent watering. This disadvantage inspired the addition of liquid polymers to water, and subsequently led to moisture retention by dust even after water evaporated, resulting in significantly reduced ultrafine particles (UFP) and extended effectiveness compared to water alone. PM_{10} and $PM_{2.5}$ levels decreased by 87% and 86% respectively when Polyethylene glycol (PEG) was added to water compared to water alone.

Effective dust suppression is very important in the workplace to protect workers' health as demonstrated in a recent study [22]. The results of this study showed that effective dust suppression reduced employees' personal exposure. Adequate dust suppression is therefore very crucial for the reduction of personal exposure, especially in the occupational environment. Process enclosure in addition to wet techniques such as water suppression, and addition of chemical substances to water are some of additional measures that are essential to control worker exposure [21, 23].

Most studies performed in this field have focussed on the effects of dust exposure, reduction of general emissions, and improvement of wet suppression method against large particles (mainly $PM_{2.5–10}$) [18,19,20,21,23,31,34], but there are not enough studies testing the effectiveness of water suppression against smaller particles (PM_1). This research contributes to closing this gap and establishing new direction and interest in submicron particle suppression strategies for control measures in quarries.

The future of PM measurement is promising because there are ways to capture and quantify submicron particles and be able to study their behaviour in terms of deposition and human exposure pathways. The study also points out the need to revisit old exposure theories and redefine risk. This may help risk managers to come up with more effective, specific, and clearly defined exposure controls. pneumoconioses such as silicosis are often only diagnosed after a long time and by that time there is nothing much that can be done because it is already too late. There is a need to direct more focus and attention on elimination strategies and understanding fine particle emissions and control offers exactly that.

2. CHAPTER TWO

This chapter appraises literature relevant to mining, quarrying, dust exposure, silica exposure, particle deposition and absorption in human lungs and dust suppression methods. The hazards of quarrying and open cast mining and factors that may increase risk exposure are discussed. The health impacts of occupational exposure to dust and mechanisms of dust release and transmission are also discussed. Silicosis as a potential disease outcome from occupational dust exposure from rock quarrying and its short-term and long-term health effects will be discussed in detail to outline the relationship between rock quarrying and silicosis. The chapter then focuses on the interaction between human exposure to dust particles and different dust particle sizes, and finally dust suppression as a method of eliminating and reducing dust emissions in the workplace, and different types of dust suppression and their effectiveness. Water suppression as a method of dust control and its effectiveness in different scenarios is also discussed at the end of the chapter to highlight the need for this study.

2.0 Literature Review

2.1 Quarrying & Open Cast Mining

Quarrying is the process of removing rock, sand, gravel, or other minerals from the ground in order to use them to produce materials for construction or other uses [24]. Quarries are the type of surface or opencast mines that may pose many different hazards to workers depending on the materials processed and procedures undertaken to produce required products. In South Africa, quarries are classified as opencast mines and are subjected to all legislative requirements imposed on the mining sector [16].

Opencast mines and quarries pose many hazards to workers and neighbouring communities and environments. In 2014, Donoghue described Various hazards that are often encountered in this environment. These included physical trauma from vehicles and machinery, noise, explosives with noise and fumes, ultraviolet exposure with risk of skin cancer, vibration, and crystalline silica in dust [25,26]. Lack of proper machinery for quarrying has also been associated with increased risk of injuries and hazards in artisanal mining in Ghana [27]. However, Oginyi concluded in 2010 that even where necessary equipment is available quarrying predisposes workers to multiple occupational health hazards, especially if not given job security, training, and awareness information on attendant dangers [28]. Other psychological hazards that were reported in this small study of sixty (60) participants in Nigeria were noise pollution, phobias, anxiety, depression, fatigue, and stress [28].

2.2 Dust Exposure

According to the South African Mining Occupational health and safety Handbook by SIMRAC, dusts are generated during the handling, pulverisation, grinding, crushing, rapid impact and decrepitation of organic or inorganic material such as rock, ore, metal, coal, and wood [16]. Dust is particulate matter that forms in the quarrying environment when big rocks are crushed, or small rocks are broken into smaller fragments that are used for different purposes [29]. It gets agitated during these processes and other processes such as haulage of materials on dirt roads around the quarry and processing plant. Wind blowing dust around stock piles also plays a role in agitating dust particles and rendering them airborne [30] and dispersed into the air. Particulate Matter (PM) has been described as a primary pollutant produced from surface mining (i.e., quarrying, and open cast mining) [31]. Rock quarrying is responsible for emission of high amounts of large and fine particulate matter. Wind and other factors such as water and humans and equipment are responsible for the transportation of dust from the source to the receptor [32]. However, wind is an important transmission medium of dust and particulate matter, responsible for a large quantities of dust transportation from the source, with other media being responsible for only a small fraction of total transported dust [33].

Many studies have focused on the transmission and dispersion of particulate matter from quarries and have demonstrated that not only workers are affected but neighbouring communities and environment also get exposed. Following emission, PM typically gets transported by wind and deposited into the nearby environment. Previously, up to 300 – 400% of quarry dust was found to have travelled downwind as far as a kilometre away from the pit, proving that it can travel very far depending on the direction and amount of wind blowing [34]. The aerodynamic size of particles, shape, and weight are major determinants of their ability to travel and their deposition into various environments [35]. In a 2019 Finnish study conducted by Sairanen, measurement of emissions and analysis of dispersion patterns of PM from 6 aggregate quarries showed high concentrations between 10-200m from the source. Crushing activities produced suspended particles and PM_{10} settled mostly near the source due to weight. Crushing comparatively produced more PM than drilling and limestone rock produced 50% less PM than granitic rock. Although PM_1 concentration was only 2% of the total emission load, it was hypothesized that it could have more health impact within the vicinity of the source (occupational setting) since its concentration had been proven to decrease with increasing distance.

Fine particulate matter is described as any dust particles smaller than 2.5 micron in diameter ($PM_{2.5}$). Small dust particles have been proven to remain suspended in the air for much longer periods compared to larger particles due to their lighter weight and smaller aerodynamic diameter. They do not always move in expected direction (downwards) because the resistance offered by airs hampers their free fall [16]. The fact that these dust particles can travel long distances means that nearby residential areas and environment could also suffer the consequent devastating effects of exposure to PM [37]. Common activities that are responsible for emission of particulate matter in and around quarries and open mines are blasting, haulage, loading, crushing, and stockpiling [38].

In quarries with secondary crushing, background concentrations of PM were detected from a 350m distance for coarse particles. Results from inside the quarry were affected by other dust sources such as hauling [36]. Haulage facilitates resuspension of settled dust particles and contributes to measured dust levels within a specified sampling area [21].

Exposure to particulate matter has been proven to have devastating impact on human health and the environment [39]. A strong association has been established between PM exposure and restrictive lung disease, reduced lung capacity, poor lung function, cardiovascular disease, pneumoconiosis, cancer, and neurotoxic effects [40]. In 2011, Nene concluded that human health effects are associated with mostly inhalable dust in the form of PM_{10} and smaller in a study conducted in Ghana. Dust exposure was also proven to have strong links to heart and lung disease, pneumonia, loss of lung function, and asthma.

The effects of quarrying and open mining on humans and the environment have been extensively studied. Naidoo described Coal Workers Pneumonitis (CWP) and chronic obstructive lung disease as some of the outcomes of exposure to South African open mines in 2002. Olusegun also demonstrated high prevalence of shock, nasal infections, and asthma in residents who live nearby granite quarries, and cough, catarrh, and sinusitis in quarry workers (occupational exposure) in 2009. This Nigerian study shows how open cast mining has impact not only in an occupational environment but also on nearby populations. Granite quarrying was also shown to pollute the environment in this study [42]. In Italy, Degan concluded in 2015 that dust emissions impair air quality and affects health and safety. This study also evaluated how the impact on quarry workers was affected by mitigation techniques designed to reduce exposure of dust emissions.

2.3 Rock Quarrying and Silica exposure

Quarries have operated for thousands of years [44]. They have contributed to the development of our world for many years [45]. Many valuable materials such as stone, sand, gravel, gypsum, salt, potash, coal, limestone, common clays, and silica [44] are produced from quarries and contribute a great deal in the development of economies and infrastructure worldwide. In South Africa, lime, limestone, and dolomite are some of the quarrying products used in four main industries: metallurgy (steel refineries), cement manufacturing, agriculture (animal feeds, fertilizer, and fungicides) and manufacturing [46]. The country depends on quarrying industry for creation of employment opportunities and sustenance of various industrial activities through many products that are generated out of quarrying activities.

Despite all the benefits of quarrying and its useful products, the biggest problem it is associated is the emission of crystalline silica. Silica is contained in over 95% of minerals contained in earth's crust [47]. It exists in two primary forms namely crystalline silica and amorphous silica [48]. Crystalline silica is the form of silica that is released by crushed stone and is present in all soils in the form of quartz and is naturally released into the environment through weathering of rocks, volcanic activities, and biogenic sources [48]. Construction and mining activities such as stone crushing are common causes of silica exposure [49]. In addition to traditional deep mining activities, small scale mining activities such as quarries and stone crushing plants are also associated with high levels of crystalline silica release and other particulate matter in their dust emissions [36].

2.4 Effects and Impact of silicosis

Silicosis, a potentially fatal, irreversible, and fibrotic pulmonary disease that develops subsequent to inhalation of large amounts of silica dust over a long time, commonly presents in occupational settings [50] and causes devastating health effects that affects former mine workers long after exposure [51]. Silicosis is a fibrotic lung disease caused by short to long-term inhalation of crystalline silicon dioxide or silica [49]. Silicosis has a long latency period and presents as acute, accelerated, and chronic disease [50]. Deposition of silica dust into the alveoli leads to chronic inflammation that is mediated by inflammatory mediators and fibrogenic factors [50, 52]. This leads to the development of silicoproteinosis over a long time accumulating in alveolar spaces and causing fibrosis that ultimately leads to respiratory symptoms (**Figure 1**). This is typically visualized as opacities and nodules on chest radiographs of affected patients.

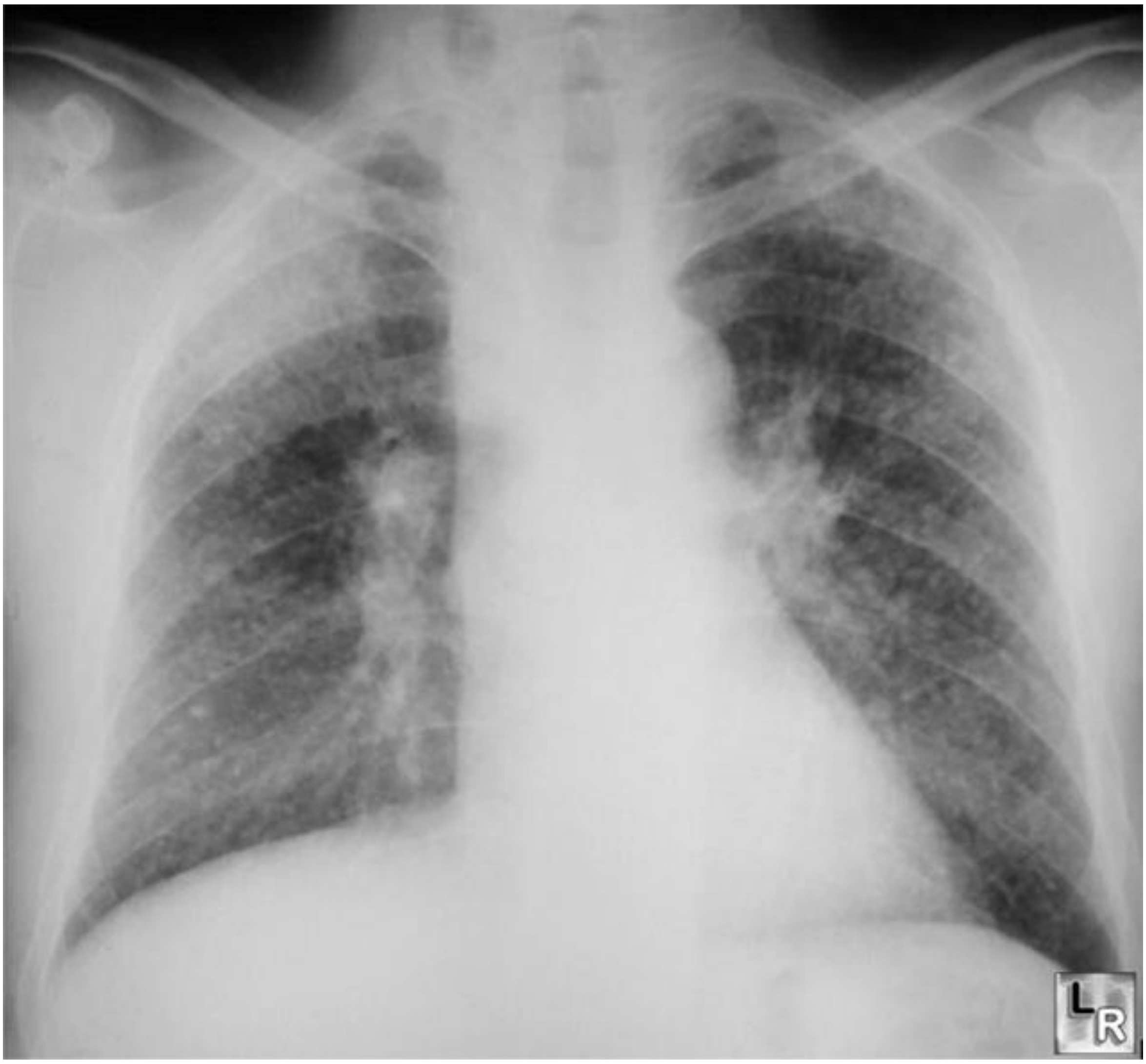

Figure 1: Lungs with Silicosis **(Source: www.learningradiology.com)**

Inhalation of silica dust leads to deposition of smaller silica particles into the alveoli of the lungs [53]. These particles are then ingested by macrophages, initiating an inflammatory response that stimulates proliferation of fibroblasts to produce collagen. Silica particles are then encased by collagen leading to fibrosis and the nodular lesions that are characteristic of silicosis [53]. Despite efforts to prevent and control silicosis, it still affects tens of millions of workers in hazardous occupational environments such as mining, quarrying, constructions, and other sectors, killing thousands of people every year [51, 54].

Silicosis presents in three different primary forms namely acute, accelerated silicosis, and progressive massive fibrosis [49, 55]. Microscopically, many different clinical and pathological varieties of silicosis have been described including simple, nodular, silicosis, silicoproteinosis (acute silicosis), complicated silicosis (progressive massive fibrosis), and interstitial silicosis [50].

Acute silicosis usually presents after a short-term exposure to large amounts of silica particles, often weeks to years (Up to 5 years) of exposure. It is characterized by microscopic appearance of pulmonary alveolar proteinosis. There is usually also interstitial inflammation and fibrosis or hyaline scars and pigment. In most cases nodules are poorly formed or absent [56]. Accelerated silicosis, on the other hand, is characterised by a longer latency period of less than 10 years of exposure and leads to early appearance of lesions and a faster progression [57]. Chronic silicosis is the most common form of the disease with exposure and latency period of 10 – 30 years, involving chronic inflammatory changes within the alveoli [50]. This chronic alveolitis may ultimately develop into fibrosis with the presence of silicotic nodules. The nodules tend to occur around respiratory bronchioles and small pulmonary arteries and in the subpleural and paraseptal areas. Progressive expansion causes obliteration and small airways and pulmonary vessels.

Progressive massive fibrosis (PMF) and simple silicosis are the two types of chronic silicosis [56]. The progression rate of disease depends on the rate of silica deposition in the lungs, as well as the total amount of crystalline silica that is retained in the lung [50]. Clinical features of silicosis include symptoms such as persistent coughing, shortness of breath, fatigue, weakness, and weight loss, with evidence of inflammation or fibrosis often discovered on examination and clinical imaging [56]. PMF may be characterized radiographically by the presence of small, rounded opacities or nodules in the lung parenchyma. Eggshell calcification may occur in lymph nodes, and eventually the disease may be complicated by development of large areas of fibrosis in the upper zones [2].

The exposure pathway (**Figure 2**) of silicosis is initiated when RCS is released in dust particles from the source. This dust is then emitted into the atmosphere where it is transported by air as a transmission medium that will disperse it based factors such as weather conditions such as windiness, humidity, and wind direction. The weight and aerodynamic diameter of dust particles are the major determinants of their transportability. Large particles often get deposited not far from the source due to gravimetric forces, while lighter and smaller particles will be transmitted far by wind. Immission occurs when the stressor (dust particles/silica) is presented to the receptor's protective membrane (respiratory organs) and get taken up through inhalation as the route of entry. From here, depending on the dose, and length of exposure, a series of interactions will take place that will determine the fate of the exposure incident. This could lead to absence of disease or any of the silica exposure outcomes described above.

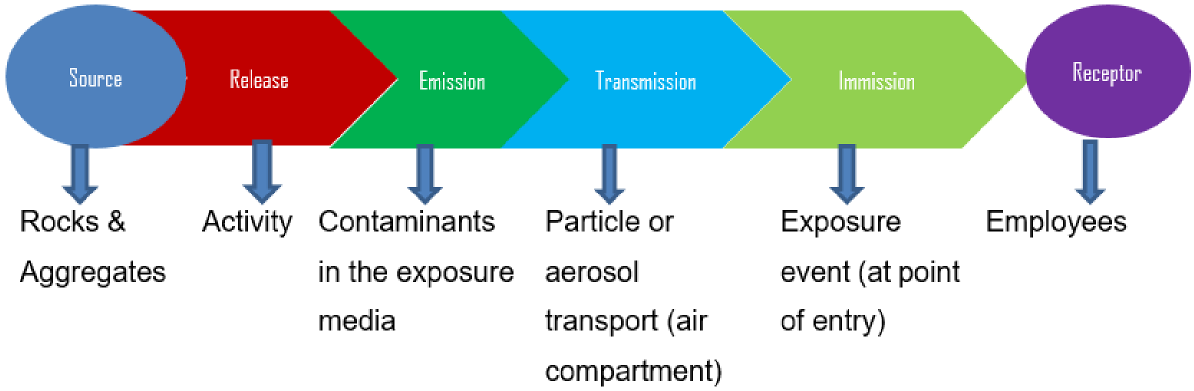

Figure 2: Exposure pathway of silicosis.

Silicosis remains a serious problem in developing nations [25]. Consequently, South Africa is one of the countries with high prevalence of occupational lung diseases including silicosis, cardiovascular diseases, and other health effects due to its vast mining activity background [41]. Silica occurs in most types of rock, sand, clay, gravel, and shale and leads to inhalation and subsequent health risks [58]. Silicosis is such a highly prevalent problem in SA that 18.3–19.9% of goldminers [51] and 9.2% – 14.7% of coalminers [41] were confirmed to be affected in 2004 and 2008 respectively. In a 2003 South African cross-sectional study by Churchyard, significant trends were found between the prevalence of silicosis and length of service, mean intensity of exposure, and cumulative exposure. High prevalence of silicosis was observed in older black workers including in-service migrant workers at a gold mine in North West Province.

In a literature review paper published in 2016 in Current Respiratory Medicine Reviews, Sen concluded that people who have been exposed to silica are more vulnerable to COPD, Asthma, TB, and fungal infections [59]. The greatest common hazard for inhaling silica is silicosis [25]. Noonan et. al. reported in 2006 that scleroderma and rheumatoid arthritis are also sequalae of exposure to silica. Silica dust has also been associated with high prevalence of other autoimmune diseases [61]. A 1999 case-control study performed amongst German stone, quarrying, and ceramics industry workers revealed that the risk of lung cancer was associated with year of and age of first exposure to silica, its duration of exposure, and latency [62]. However, the same study found no direct association of exposure to crystalline silica and lung cancer. Other health problems that have been associated with silicosis in addition to autoimmune diseases are kidney diseases [63].

In 2012, Chen observed standardized mortality ratio for different causes among workers exposed to respirable silica concentrations equal to lower than 0.1mg/m^3. Silica dust accounted for 15.2% of all deaths in this study after confounders such as smoking were eliminated. It was estimated that 4.2% (231 104) of deaths among Chinese workers were attributed to exposure to silica dust. He subsequently concluded that long-term silica exposure was associated with increased mortality amongst Chinese workers.

Thongtip also demonstrated the impact of silica dust exposure in neighbourhoods in 2020. The average silica concentrations of all nearby stone factories were higher than recommended limits. The study showed that the subjects' age, income, occupation, smoking, distances, and number of respiratory symptoms were associated with effects of silica exposure. The subjects who lived closer to stone factories (50m) had poorer outcome than those whose distance from stone factories was more than 100m. This means that community members residing closer to quarries are also at risk of exposure to the silica dust released into the environment. Duration of exposure to silica dust, mean intensity of exposure, and cumulative exposure have also been linked with the prevalence of silicosis [51] in a study performed amongst mine workers in South African miners in North West province. The mean length of service was 21.8 years (range 6.3-34.5), the mean density of exposure to respirable dust was 0.37 mg/m^3 (range 0-70) and of quartz 0.053 mg/m^3 (range 0–0.095).

Silico-tuberculosis is another important manifestation of silica exposure, especially in Africa [25]. Some research papers have also associated silica exposure with tuberculosis (silicotuberculosis). In 2018, Pretorius concluded that the interaction between inadequate silica dust control, high burden of HIV/Aids and Tuberculosis (TB) control, and their subsequent negative impact on occupational hygiene control measures and medical surveillance programmes, could lead to increased risk for TB, even long after exposure ends. According to research silica exposure and Human Immunodeficiency Syndrome (HIV) have a synergistic effect on the development of tuberculosis [16,51,66]. Despite administration of the same treatment regimens as for community acquired TB, with similar treatment outcomes for silicotuberculosis, the mortality associated with silicotuberculosis may be higher compared to TB patients without silicosis [16]. Silicosis was declared by Elgstrand as the occupational respiratory disease of major concern in the South African gold mining industry in 2007 when autopsy silicosis rates rose to 32%. In 2019 former and current gold miners who had/have clinical evidence of exposure to silica were awarded 5 billion Rands in compensation in a landmark judgement against gold mines [67]. This demonstrates that the impact of silicosis is well-recognized by the South African Government and may expose mining companies to tougher sanctions in the future.

In the USA, the cumulative risk of death from silicosis with an exposure of 0.1 mg/m^3 between the age of 20 and 65 was estimated at 13 per 1000 [68]. At half the exposure rate the cumulative risk of death was estimated to be 6 per 1000, demonstrating the direct association of silica exposure concentration with mortality amongst mineworkers. Despite the clearly demonstrated association of the risk of lung cancer and the year of and age at first exposure to silica, duration of exposure, and latency, no association between exposure to crystalline silica and lung cancer could be demonstrated [62]. Despite this, Cassidy and Poinen concluded in 2007 and 2016 respectively that the risk of lung cancer is higher with silicosis. In the Cassidy study the risk was most apparent at the odds ratio of 1.37 (95 CI, 1.14-1.65). This study evaluated the exposure to RCS due to the artificial stone processing, materials that contain very high percentages of this hazardous substance (from 30–90%) [71], United States Department of Health and Human Services also reports that people who breathe PM_4 crystalline silica long term could be at risk for health problems like silicosis, lung cancer, and other respiratory, kidney, and autoimmune diseases [48].

2.5 Particle deposition in lungs

Particulate Matter (PM) is a type of air pollution that is generated by human activities and can travel long distances in the atmosphere and cause a wide range of diseases, and significant reduction of life expectancy [72]. It is one of the most dangerous pollutants in atmospheric air [73], consisting of solid and liquid particles suspended in air, and it can consist of organic and inorganic molecules [74]. Particles vary in size, composition, and origin [72]. Particles are classified by their aerodynamic properties because, among others, these properties determine the transport and removal of particles from the air and their deposition within the respiratory system [72]. The following terminology is commonly used to describe particulate matter:

- Total Suspended Particulates (TSP): comprises all airborne or suspended particles.
- PM_{10}: particulate matter with an aerodynamic diameter <10µm.
- PM_4: particulate matter with an aerodynamic diameter <10µm.
- $PM_{2.5}$: particulate matter with an aerodynamic diameter <2.5µm.
- $PM_{1.0}$: particulate matter with an aerodynamic diameter <1.0µm.

The coarse fraction comprises of particles with diameter between 2.5µm and 10µm, while fine PM (FPM) generally refers to particles smaller than 2.5µm. Submicron particles belong to the group with diameter smaller than one micrometre, whereas a portion of submicron group smaller than 0.1µm is commonly referred to ultrafine particles (UFP) [72].

PM is typically composed of a mixture of chemicals and that is strongly dependant on source characteristics. The following chemicals have been identified as constituents of PM in different studies: silica, antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, selenium, and carbon [75]. Most of these metals are also known to be present in coal [76]. In a study by Peng in 2016 silica, aluminium, and cadmium were found to be major elements of $PM_{2.5}$. In a recent study by Hu (2022) the mineralogical composition of submicron particles in two different soil types was dominated by chlorite (Al-Si-O-Mg), kaolinite (Ai-Si-O), and quartz (SiO).

Quarrying activities such as blasting, drilling, crushing rock, loading, road haulage, and stockpiling, result in ground disturbance and dust resuspension which lead to agitation of fugitive dust from mining surface and roads with its particulate matter being one of the most important air pollutants [43, 79,80]. However, regulation in most countries include only PM_{10} particles, and no regulatory action had been adopted yet in 2015 concerning the potentially more harmful particles, submicron and ultrafine particles (<100nm diameter) [75]. This could be mostly because until recently it has been very difficult to detect and quantify smaller particles [81]. However, this particle size distribution tends to account for a much higher percentage of the TSP [82]. In Wuhan, the proportion of PM_1 contained within PM2.5 was roughly 90%, directly proving that submicron particles may be the largest component of PM2.5 in some circumstances. In studies in Poland and China, PM1 contributed 69-75% of PM2.5 in both indoor and outdoor environment [83,84]. These studies demonstrated that a major portion of PM2.5 is submicron particles, necessitating more interest in studying effects of PM_1 [79,82], focussing on mainly the bigger particles means the smaller particles that are actually more respirable may be neglected.

In 2019, Mainka concluded that PM_1 is not subject to air quality standards nor WHO recommendations, as compared to $PM_{2.5}$ and PM_{10}, despite PM_1 having been shown to have a higher potential to cause harmful health effects than coarse particles [85]. This PM is more likely to reach deeper into the respiratory system carrying with it more toxins from anthropogenic emissions as shown in Figure 3 [85]. Recently, more interest has been shown to submicron and ultrafine particles characterized by particle number and surface area concentration [86], as opposed to coarse fraction PM (characterized in terms of the mass concentrations). The interest of the scientific communities to study submicron particles only increased recently [87]. Lee 2006 concluded that exposure to fine particles have attracted increased attention in urban areas due to their association with morbidity.

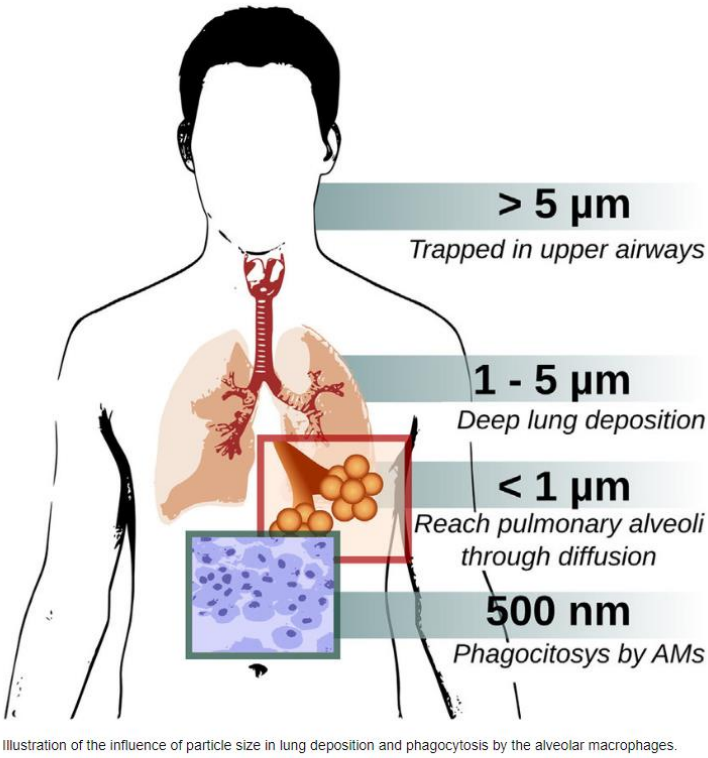

Figure 3: Lung deposition of different particle sizes

Inhalation as an exposure route presents an opportunity for FPM to penetrate the respiratory system. PM_1 is deposited in the alveolar regions of the lungs due to its smaller aerodynamic diameter [73,89] with up to an adsorption efficiency of 60-80% [90]. The link between PM and decreased lung function, aggravation of respiratory diseases, and increased hospitalization for the elderly has also been reported in this study. Exposure to fine dust particles could causes short-term effects such as eye, nose, throat and lung irritation, coughing, sneezing, runny nose, and shortness of breath [75,89]. Exposure to fine PM is also associated with reduced life expectancy [75]. Patra also reported that $PM_{2.5}$ and PM_1 are inhaled very deep into the lungs, while PM_{10} or smaller particles result in poor human health [31]. Asbestos, silica, mica, beryllium, copper, and iron are some of the chemical composition elements found in dust that are responsible for adverse human health effects. This 2016 systematic review also found a strong association of airborne PM with adverse health consequences such as respiratory disease, cardiovascular (CVS) disease, pneumoconiosis, cancer, and neurotoxic effects.

Exposure to PM can affect lung function and worsen medical conditions such as asthma and heart disease [91]. Increased daily exposure to PM2.5 has been linked with increased respiratory illness, and cardiovascular admissions, emergency department visits and deaths [92]. Studies also suggest that long-term exposure to fine particulate matter may be associated with increased rates of chronic bronchitis reduced lung function, and increased mortality from lung cancer and heart disease [93]. In a 2017 study by Oudwater it was found that quarry workers exposed to PM had evidence of decreased lung function and renal pathology. Chen in 2021 demonstrated in a two-year panel study showed that ultrafine particulate matter was significantly associated with respiratory conditions.

2.6 Dust Suppression

The Occupational exposure limit for inhalable dust has been set at $0.1mg/m^3$ [96]. While this has helped for countries and workplaces to enforce compliance there is a major problem with the quantification and measurements of dust. Until recently, the scientific interest in PM was mostly in effects of $PM_{2.5}$ to PM_{10}, submicron particles were not routinely tested for due to lack of accurate measuring instruments or scientific interest in their effects. To this end when OEL levels are determined or interpreted, it is mostly confined to FPM and larger particles. There could be large amounts of UFP’s, and submicron particles not detected because we do not routinely test at that size level. Governments have also not imposed measurements of UFP’s and submicron particles, and do not enforce breakdown of particle distributions.

There are many dust suppression methods that have been described and tested over the years to reduce both occupational and environmental exposure [97]. Many studies have also demonstrated the impact of PM and dust dispersion into neighbouring communities [98]. Dust suppression methods are generally classified into dry and wet methods. Water suppression and dry fogging have been developed to address the particulate emissions problem within mining and construction industries [99].

Water Suppression or wet suppression is a method through which water is used to control the emission of particulate matter into the air/atmosphere [100]. Water spray applications are some of the principal means of controlling airborne respirable dust in coal mines [101] and other types of mining. This method has been proven effective in reducing PM_{10} in high winds [100] and emissions from the surface of dust sources [23]. Watering raises moisture content in dust sources and agglomerates dust particles via the capillary force of water molecules [23]. This leads to dust particles becoming larger, heavier, and unable to move with ease. The Water Suppression Method (WSM) has been proven to effectively control emissions of larger particulate matter (PM_{10}) in mining and construction industries. It is one of the oldest and cost-effective methods for controlling fugitive dust. It does so by increasing the diameter and weight of particles, making them less likely to float in the air. Fitz et. al demonstrated in 2000 the effectiveness of water against PM_{10} under windy conditions. Watering was proven effective against PM_{10} at wind speeds up to 18 metres per second (m/s).

Effective dust suppression is very important in the workplace to protect workers' health as demonstrated in a recent study [22]. Many studies have shown that effective dust suppression reduces employees' personal exposure. Adequate dust suppression is therefore very crucial for the reduction of personal exposure, especially in the occupational environment. Over the years we have learned that large dust particles deposit not far from the source and lodges only in the upper respiratory tract. This is shown in Figure 3. They do not easily reach the lower airways and therefore are able to be cleared through the lungs' natural clearing mechanisms. It has also been shown that the current water suppression methods are very effective against larger particles, but not really smaller ones. PM_1 was traced far from source despite dust suppression measures in one study [102]. This meant that despite the use of water as a method of suppression, these fine particles were still able to travel. Dust formed in quarries that perform tertiary crushing was also proven to be capable of spreading to a wider diameter (350m). Most of the studies performed in this field have focussed on the effects of dust exposure, reduction of general emissions, and improvement of wet suppression method against large particles (mainly $PM_{2.5-10}$), but there is not enough literature testing the effectiveness of water suppression against smaller particles (PM_1).

The fact that we now have instruments that are able to detect fine and ultrafine particles means that we can use them to study the impact of these particles unlike in the past when we were only limited to larger particles. This study seeks to particularly focus on the smaller particles that may not be controlled by water suppression and inspire development of new solutions that will specifically target the elimination of particles smaller than 1 micron (PM_1). It has been demonstrated that higher concentration of PM_1 particles moved up due to low settling velocity compared to larger particles in a study that determined dispersion of various particles in an open pit copper mine and lingered in the air for much longer [103]. This was despite the fact that the overall dust concentration decreased from 45-49% to 13-16% with decreasing depth. This meant that even in the presence of common dust suppression methods, these small particles were still capable of moving and finding their way into human lungs and causing adverse health effects as outlined above. It is therefore important to put more emphasis on smaller particles when assessing the effectiveness of dust suppression methods to ensure that potential impact is met with equally effective methods that can limit exposure and prevent devastating health effects.

3. CHAPTER THREE

This chapter begins with the description of the study location and how dust emissions are generated from rock crushing and other related processes. It further discusses sampling and data management in terms of different stone aggregate treatment scenarios in the plant and how the data was collected, analysed, and stored. The chapter then ends with the discussion of various quality control aspects that were employed in this research.

3. Methods and Materials

3.1 Description of the study area and emissions process

The quarry is located in Ekurhuleni Metropolitan Municipality, east of Johannesburg. It produces stone aggregates through 3 crushing phases, and the stones and sand are supplied to clients in different sizes, mostly the construction and rail industry. **Figure 4** (© Google Maps) outlines the quarry in relation to the neighbouring residential areas.

Figure 4: Aerial view of the Quarry (Source: Google Maps)

The crushing of dolerite rock is achieved through three stages namely primary, secondary, and tertiary processing. The earthmoving equipment and loaders feed big rocks into the jaw crusher which crushes big rocks into 150mm stones and delivers the crushed aggregates (primary product) into a stockpile. These aggregates are then conveyed into the secondary processing area which is fitted with a screen that separates the 57mm stone chips from the larger stones fed into it (secondary product), and tertiary phase further crushes them into various particle sizes (<6mm, 6.7mm, 9.5mm, 13mm, 19mm, etc.). Dust suppression is traditionally achieved through water suppression during the last two phases. This study aimed to measure the PM levels emitted during different phases of the crushing cycle, both before and after different applications of water as a suppression method.

3.2 Data Collection

Monitoring strategies and location:

Data was collected during primary, secondary, and tertiary phases, as well as the office block, as outlined in the objectives. The following diagram indicates data collection points in the plant (**Figure 5**).

Figure 5: Data Collection Points (Source: Google Maps)

The first sample was collected over an hour at the at the end of the primary treatment area. This is a dry process that results from the breakdown of rocks by the jaw crusher and the primary 150mm screen. The crushed rock is approximately 150mm in size and stockpiled between the primary and secondary area. From here it will be moved into the secondary processing area with a 57mm screen by an underground conveyor belt. The sampling point is at the point where the conveyor emerges from underground tunnel and ascends into towers to deliver stones into the crushing and screening area. Large amounts of dust are emitted from this point and visible to a naked eye and this is what made it the best point to sample from. The sampling tube was placed alongside the conveyor at the height of 1500mm assuming an average human respiratory zone, and 30cm away from the conveyor to prevent damage from the falling rocks.

The second sampling point was at the end of the secondary screen where stones larger than 57mm are conveyed to tertiary screens for further crushing. This screening tower is fitted with water sprinkler system (dust suppression) and stones leaving this area have been subjected to moisture to reduce dust emissions. This was also the perfect point to sample dust from the source that has been treated with water suppression. The sampling tube was placed alongside the conveyor, 30cm away from the conveyor to prevent falling stones from crushing the equipment, at the height of 1500mm.

The third sampling point was set after the 19mm screen after the stones from the secondary processing area have been broken down into a 19mm product. This product then flows into a water bath and gets washed up for dust and other small particles in a pool of water to prepare it for final stockpiling before collection by clients. From here some of the stones will go into the tertiary crusher and smaller screens to produce smaller aggregates and ultimately sand. The stones leaving the bath are considered very clean and free of dust as a result of the rinsing process. Here the sampling tube was also placed 30cm away from the conveyor belt that transports these clean stones into the final storage, and at the height of 1500mm for uniformity and fair comparison with the first two samples.

The fourth sampling point was in front of the office block some 200m away from the crushing plant. The purpose was to demonstrate possible movement of dust particles from the emission source to the offices where employees usually spend most of their shift period, without any personal protective equipment.

The following sampling scenarios were therefore created:

Scenario 1: Activity without intervention.

Monitoring for 1 hour at 5 second intervals. Measurements were carried out continuously over an hour. No intervention (water suppression) was applied at this point and the sample represents true emissions from the source point.

Scenario 2: Activity with intervention (water suppression)

Monitoring for 1 hour at 5 second intervals. Measurements were carried out continuously over an hour. The intervention (water suppression by sprinklers) was applied at this point and the sample represents emissions of particulate matter following primary intervention.

Scenario 3: Activity with further intervention (water bath)

Monitoring for 1 hour at 5 second intervals. Measurements were carried out continuously over an hour. The intervention (water bath) was applied at this point and the sample represents emissions of particulate matter following secondary intervention.

Scenario 4: Activity away from the source with possible occupational exposure

Monitoring for 1 hour at 5 second intervals. Measurements were carried out continuously over an hour. The was no intervention applied at this point and the sample represents emissions of particulate matter available for uptake by the receptor (workers).

3.3 Description of the data collection tool

Nanozen (Nanozen Industries, Canada) was used to collect dust (particulate matter) samples. The instrument was fitted with sampling probe of 15mm in diameter and length of 1 metre (Teflon tube). 37mm cassette was used to attach $PM_{2.5}$ cyclone. PM Cyclone was used to isolate larger particles from entering equipment. Nanozen internal platform is sensitive to backlogs and overload on the internal filters. The $PM_{2.5}$ cyclone operates efficiently at 2.7l/min at 50% cut off point. Consequently, the Nanozen has a fixed flow rate of 1 l/min. A sampling probe was extended at a height of 1.5m, assuming a breathing zone circumference of the receptor.

Instrument limitations: The instrument cannot differentiate between particles and aerosols. The instrument is able to measure in real-time.

3.4 Data Analysis

Basic comparison using mean, standard deviations, number concentration and average mass concentrations before and after water suppression were performed to interpret results. Microsoft ® Excel ™ (Microsoft 365) was used to perform analysis after data were transferred from the measuring device. Efficacy of dust control measure (method) was determined by deriving the mass concentration and number concentration for the four scenarios.

3.5 Data Management

Data from Nanozen was exported into a computer software interface and converted into MS Excel spreadsheet (Microsoft® 365), cleaned, and arranged according to variables such as Particle number concentration, mode, mean, and mass concentration. Outliers such as missing data points and overestimates were removed. Data has been stored securely on a computer with a password and backed up in a cloud storage which can be accessed for a maximum period of 4 years.

3.6 Quality Control

The sampling devices were calibrated in the Occupational Hygiene Laboratory at the University of Witwatersrand. The Nanozan was thoroughly cleaned before use and stored securely in its casing for safety. The equipment was only handled and operated by the researcher accompanied by quarry team members for clarification of processes and sampling points. To ensure that good quality standards were adhered to, the researcher ensured that the height of the sampling tube and proximity to the emission points were equal across all the four scenarios. This was set at 1500mm height, assuming the breathing zone for an average human to closely simulate the exposure concentration under natural conditions. The samples were immediately uploaded into the computer for analysis and stored on the local drive and cloud under strong password security measures.

4. CHAPTER FOUR

Chapter 4 details all the findings of the study in terms of different objectives outlined early in this report. Results will be presented in figures and tables focusing on mass concentrations and number concentrations of dust emissions at different treatment areas and office block as a control. These data are then used to compare dust emission levels at different sites and effectiveness of water suppression strategies employed at different treatment areas in terms of general emission mass and number concentration, and specifically also look at the suppression of various submicron particle size bins.

4. Results

4.1 Results for objective 1: No water suppression

As the underground conveyor moves the stones from the primary treatment stockpile dust is agitated and emerges out of the conveyer belt tunnel. The dust consisting of particles of different diameters is emitted into the environment without any dust suppression intervention. The average mass concentration of 460.2 µg/m^3 (±486.3) is emitted from the tunnel over 1 hour (74.6 minutes). The composition of this dust reflects a large amount of submicron component which accounts for more than half of the particle number concentration (58.7%).

Figure 6 reflects real-time emissions rate of dust in terms of mass concentration. In this figure, it can be demonstrated that the emission rate is variable over time with peaks around 1st, 3rd, 14th, 20th, 24th, 44th, and 57th minute. As it can be seen the mass concentration ranges between 16 and 3100 µg/m^3, with an average of 460.20 (±48.63) over a period of over 1 hour (t=74 minutes). During this treatment phase large amounts of dust are released uninterrupted without any interventions. This phase recorded the highest emissions of all stages in terms of mass concentration.

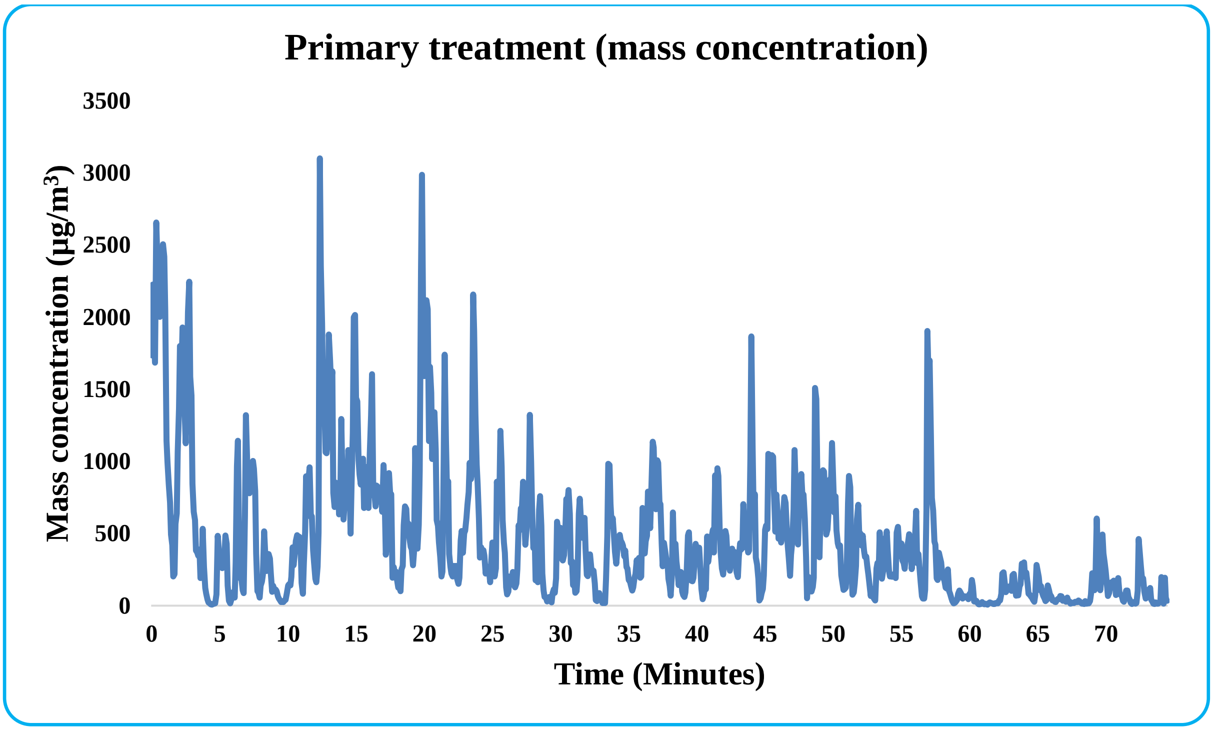

Figure 6: Mass concentration during primary treatment.

The number concentration emission rate during primary treatment phase correlates directly with the mass concentration in terms of peaks and troughs. This indicates that the number concentration rate is directly linked with mass concentration rate. The emission rate ranges between 50 million and 717 million dust particles in various bin sizes, with an average of 221762329.28 (±136958.7). **Figure 7** demonstrates number concentration emission rates over the same period of 74 minutes.

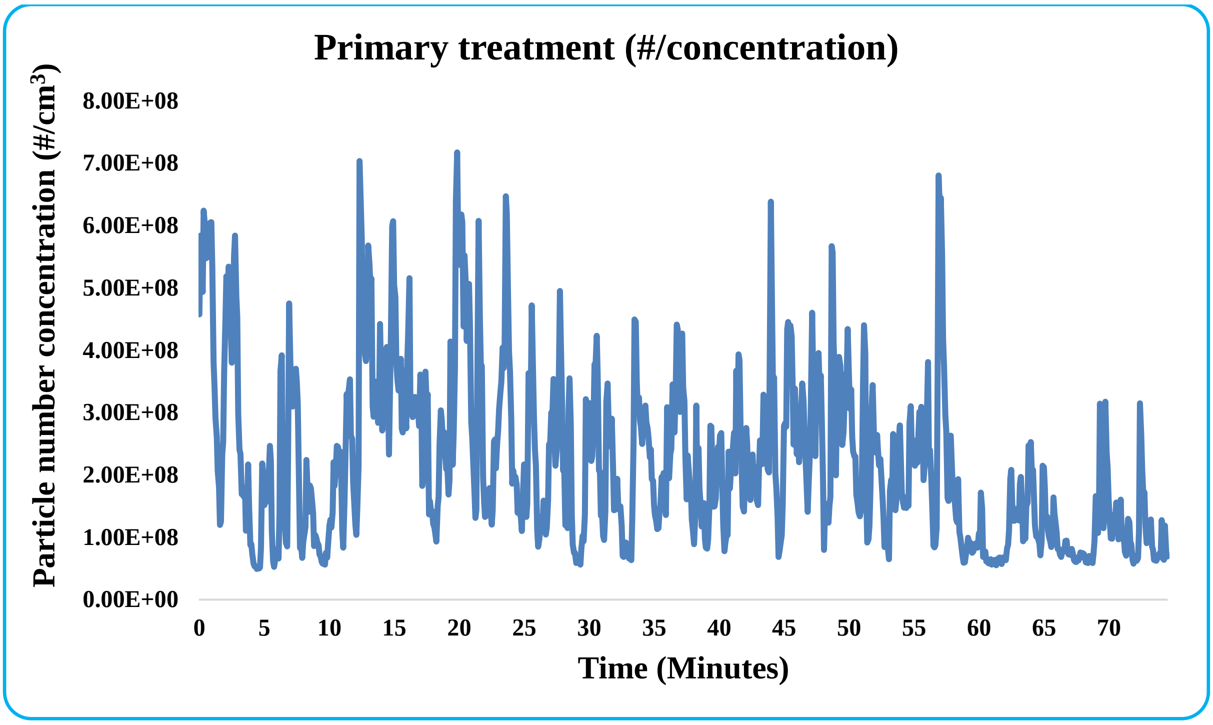

Figure 7: Particle number concentration during primary treatment

Figure 8 demonstrates the lognormal distribution of mass concentration results, skewed to the left. The larger particles contribute a large portion of the total mass concentration of emissions in the primary treatment area. The highest concentration of dust as demonstrated is contributed by the particles in the 2.24 to 4.37µg/m^3 ($PM_{2.5}$ to PM_4) range, the respirable component of particulate matter.

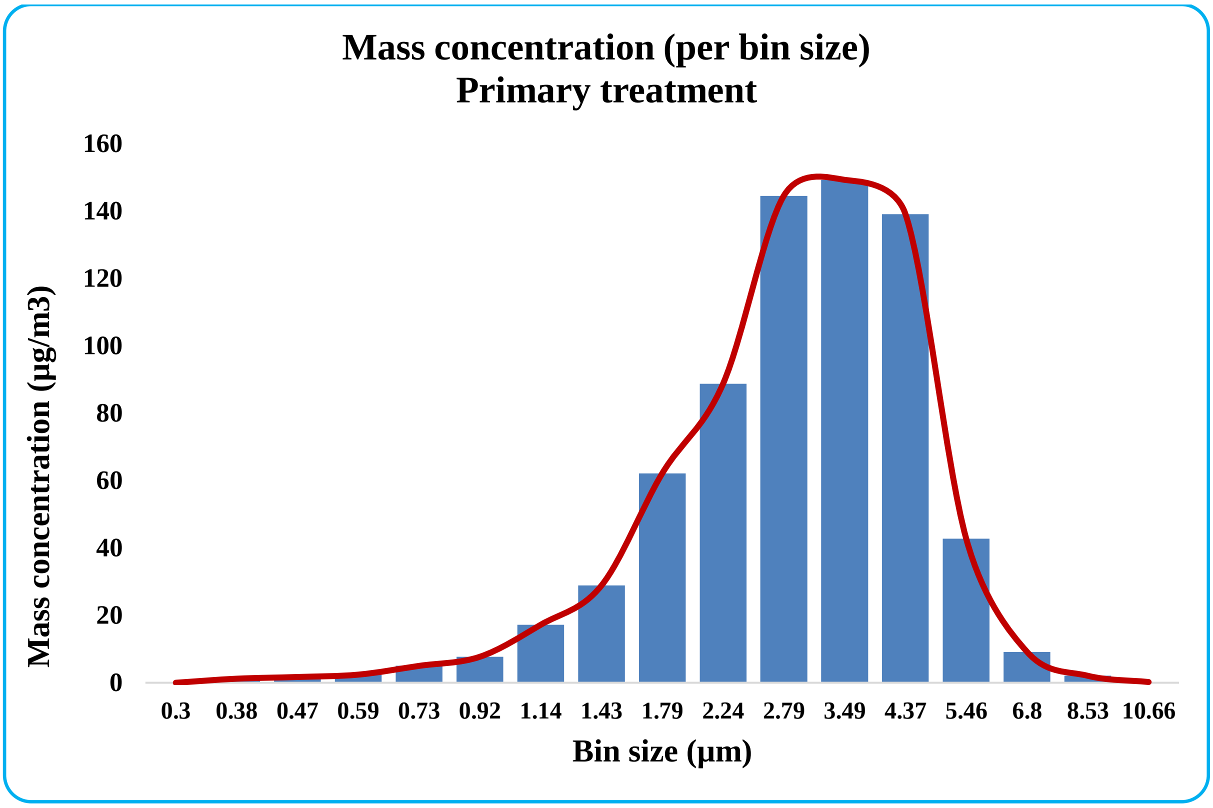

Figure 8: Mass concentration per bin size in the Primary Treatment Area

Although the mass concentration data is skewed to the left (**Figure 9**), the number concentration data is skewed in the opposite direction while also showing a lognormal distribution. This indicates that despite the larger bin size particle carrying the most weight the smaller bin sizes are in much higher numbers, contributing the highest number concentration of the particle emissions. Most of the particle composition is in the submicron range, accounting for approximately 60%.

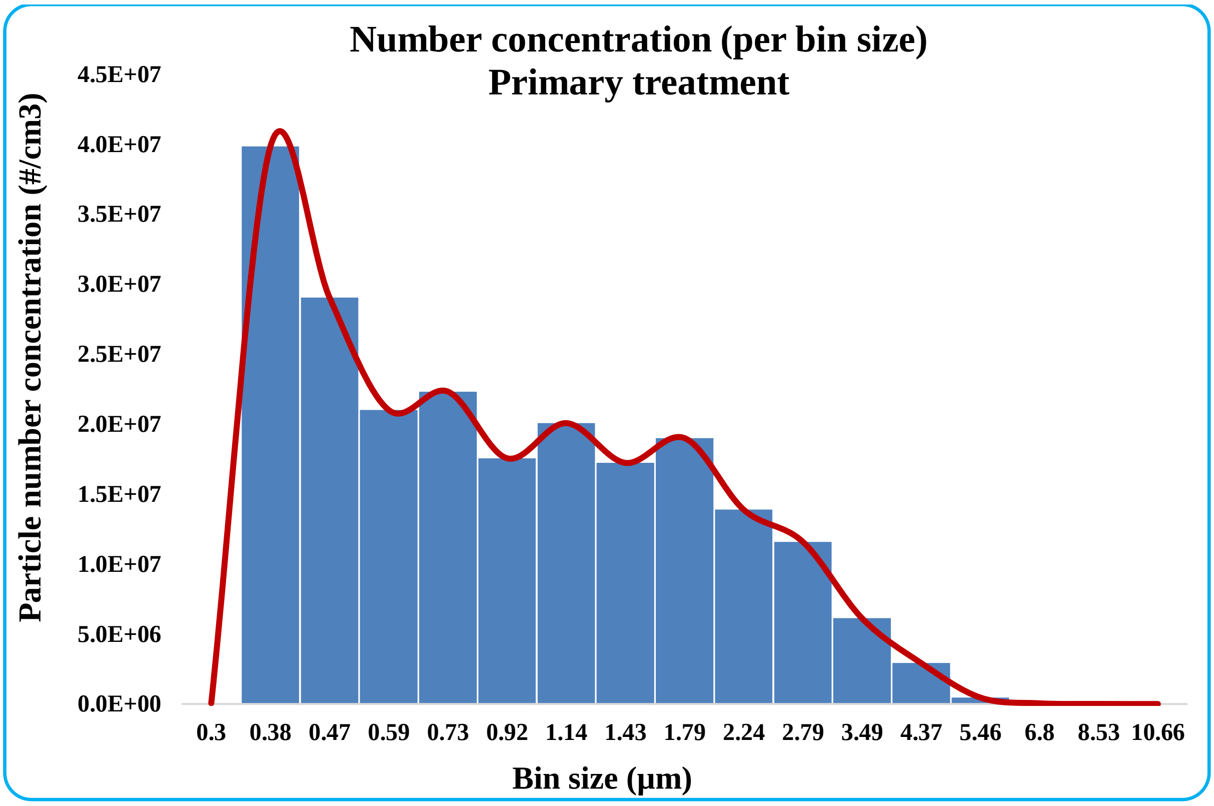

Figure 9: Number concentration per bin size in the Primary Treatment Area

Table 1 summarizes the findings of particle number and mass concentration as percentage contribution for the various size bins. It can be shown that a larger proportion of total mass concentration (74.3%) is contributed by respirable particles in the 2.24 to 4.37 ($PM_{2.5}$ – PM_4) range. However, as indicated above, the submicron particle range is responsible for a large portion of the total number concentration (58.7%). This is the most important bin size range in our study due to its potential health impact as shown in Figure 3. The table below also indicates that the total average of 220 million (±136958) particles per cubic centimetre at a calculated total mass concentration of 720µg/m^3 (0.7mg/m^3) were emitted during the 74-minute period.

Table 1: Mass and Number concentrations per bin size in Primary Treatment Area

Bin size (µm)	#/Conc.	Mass Conc.	% Number contribution	% Mass contribution
	#/cm^3	µg/m^3		
0.3	6.1E+04	0.0002	0.03	0.00
0.375	4.0E+07	1.20	18.01	0.17
0.468	2.9E+07	1.71	13.13	0.24

0.585	2.1E+07	2.41	9.50	0.34
0.732	2.2E+07	5.01	10.09	0.71
0.915	1.8E+07	7.70	7.94	1.10
1.144	2.0E+07	17.19	9.07	2.45
1.430	1.7E+07	28.84	7.79	4.11
1.788	1.9E+07	62.14	8.59	8.85
2.235	1.4E+07	88.73	6.28	12.64
2.793	1.2E+07	144.56	5.24	20.59
3.492	6.1E+06	149.28	2.77	21.26
4.365	2.9E+06	139.12	1.32	19.82
5.456	4.6E+05	42.74	0.21	6.09
6.821	5.0E+04	9.17	0.02	1.31
8.526	5.8E+03	2.06	0.00	0.29
10.658	3.1E+02	0.21	0.00	0.03
Sum	**2.2E+08**	**702.07**	**100**	**100**

4.2 Results for objective 2: Water suppression via sprinkler method

After the aggregates have been conveyed into the secondary treatment screening where water sprinklers are fitted to suppress dust, the conveyor belt transports the wet rock to the tertiary treatment area where it will be crushed into smaller aggregates. The composition of the sample as per **Figure 10** below demonstrates that the average and total mass concentration of the emissions in the secondary treatment area has been reduced compared to the primary treatment area emissions. The graph also shows an increase in mass concentration activity between 12-32 minutes and 65 minutes. This is due to variations in emission levels resulting from rock crushing.

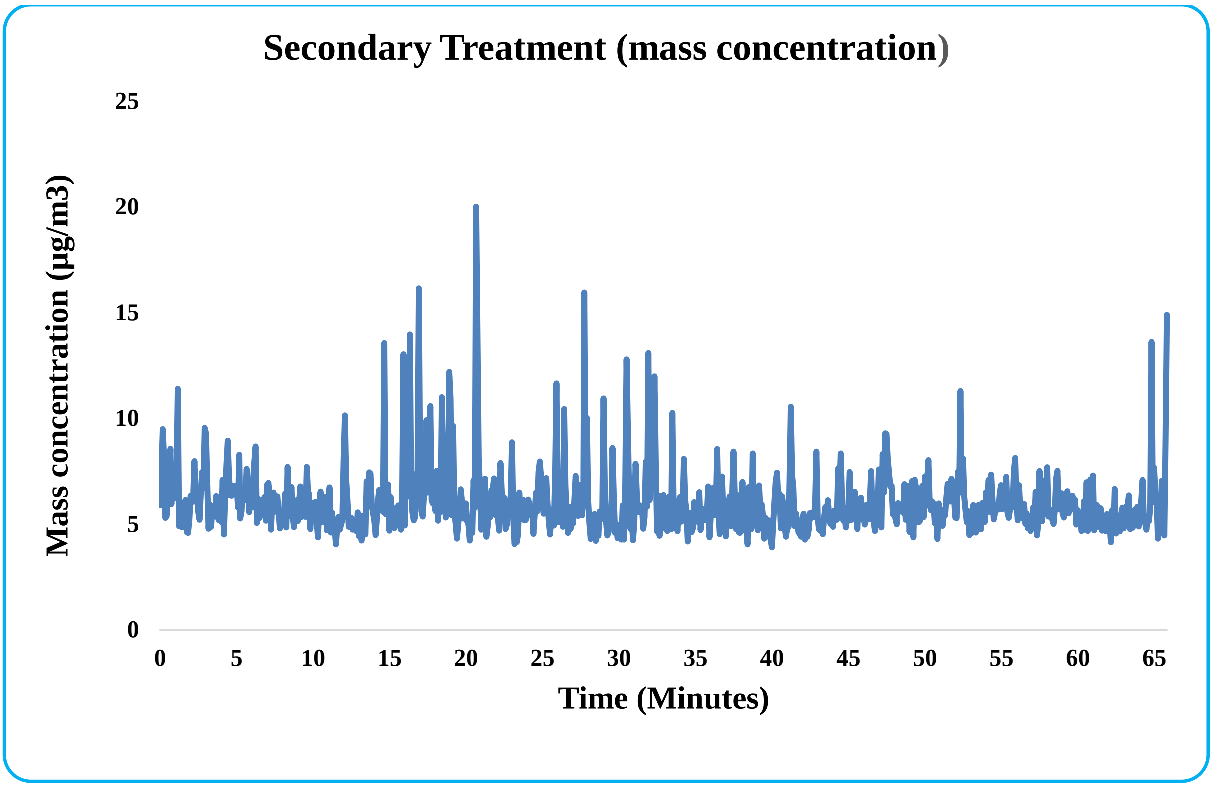

Figure 10: Mass concentration in the Secondary Treatment Area

Although the average number concentration in the secondary treatment (shown in **Figure 11**) has been greatly reduced due to water suppression, the real-time concentration still remains high within the 46.9 million to 81,2 million particles per cm^3 with an average of 60.9 million (±552879). However, the number concentration peaks are observed in the 1^{st} to 10^{th} minute and 54^{th} to 55^{th} minute time range due to the mass concentration contribution shift as shown in **Figure 12**.

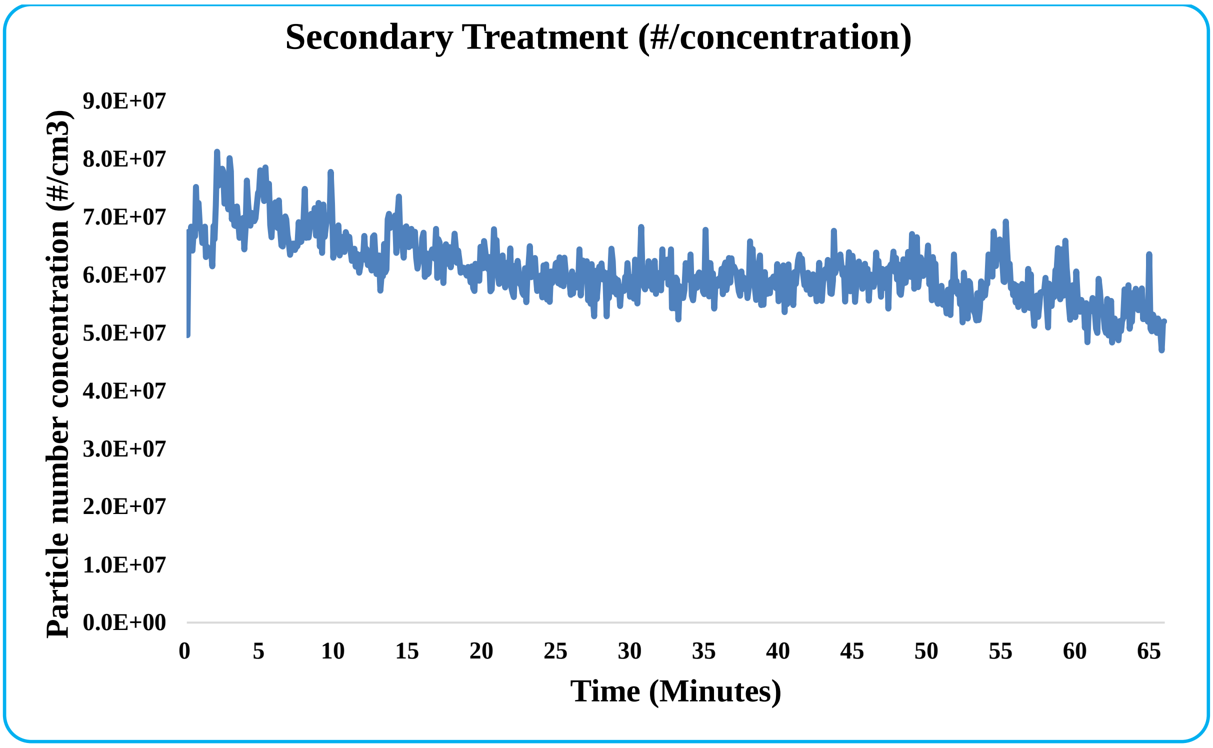

Figure 11: Number concentration in Secondary Treatment Area

As indicated above, smaller submicron particles in secondary treatment **(Figure 12**) contribute a larger percentage of the total mass concentration mass compared to a dry treatment area where most of the weight is contributed by the larger $PM_{2.5}$ to PM_4 particles. In this treatment area the submicron range makes up 41.9% of the total mass concentration compared to 31.3% contributed by the $PM_{2.5}$ to PM_4 range. The data here shows a bimodal distribution with skewness to the left.

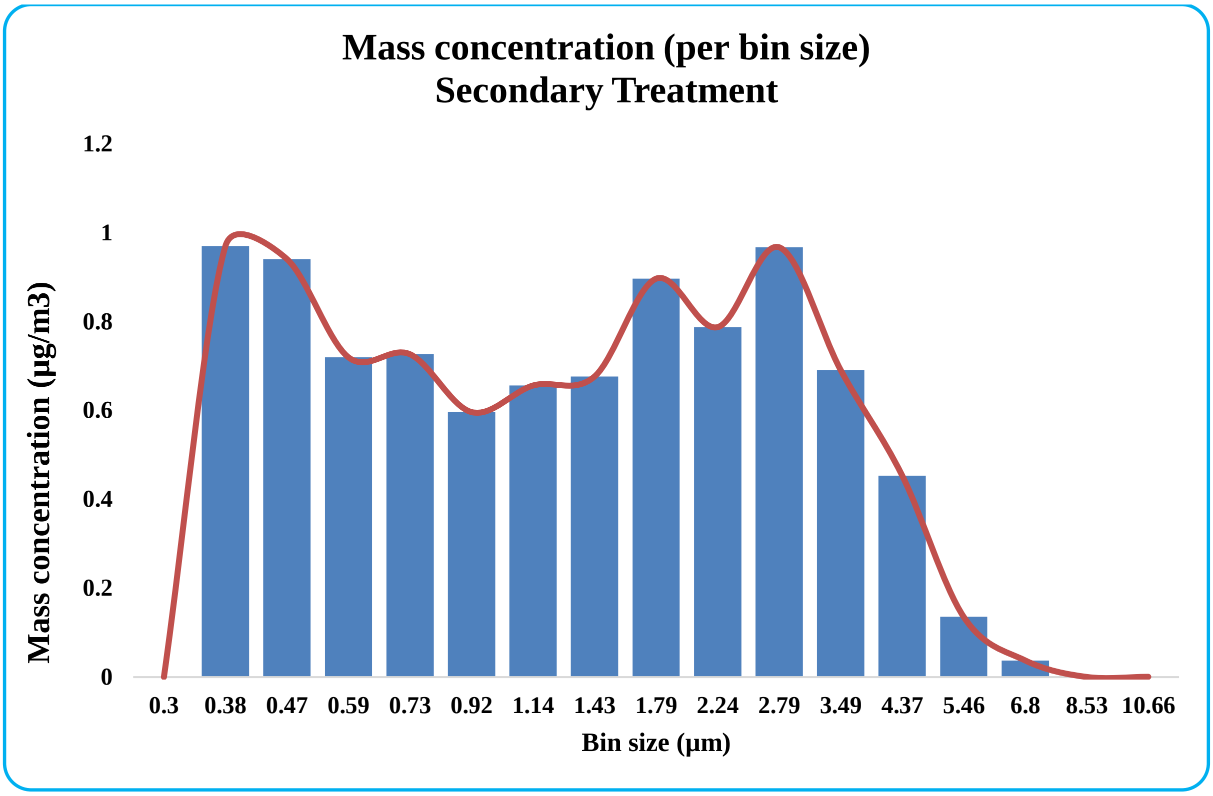

Figure 12: Mass concentration per bin size in the Secondary Treatment Area

In **Figure 13**, a large portion of dust particles emitted from this sampling area after exposure to water sprays are in the submicron range (95%) while the rest of the emissions are in the $PM_{2.5}$ range, indicating that the PM_4 and other larger particles are highly suppressed during the wet treatment. Most of emission are in the smaller particle range, causing the data to be skewed to the right. This means that most of the larger particles have been suppressed by wetting and only smaller submicron particles are emitted by the aggregates loaded onto the conveyor belt in transit to the tertiary crushing tower.

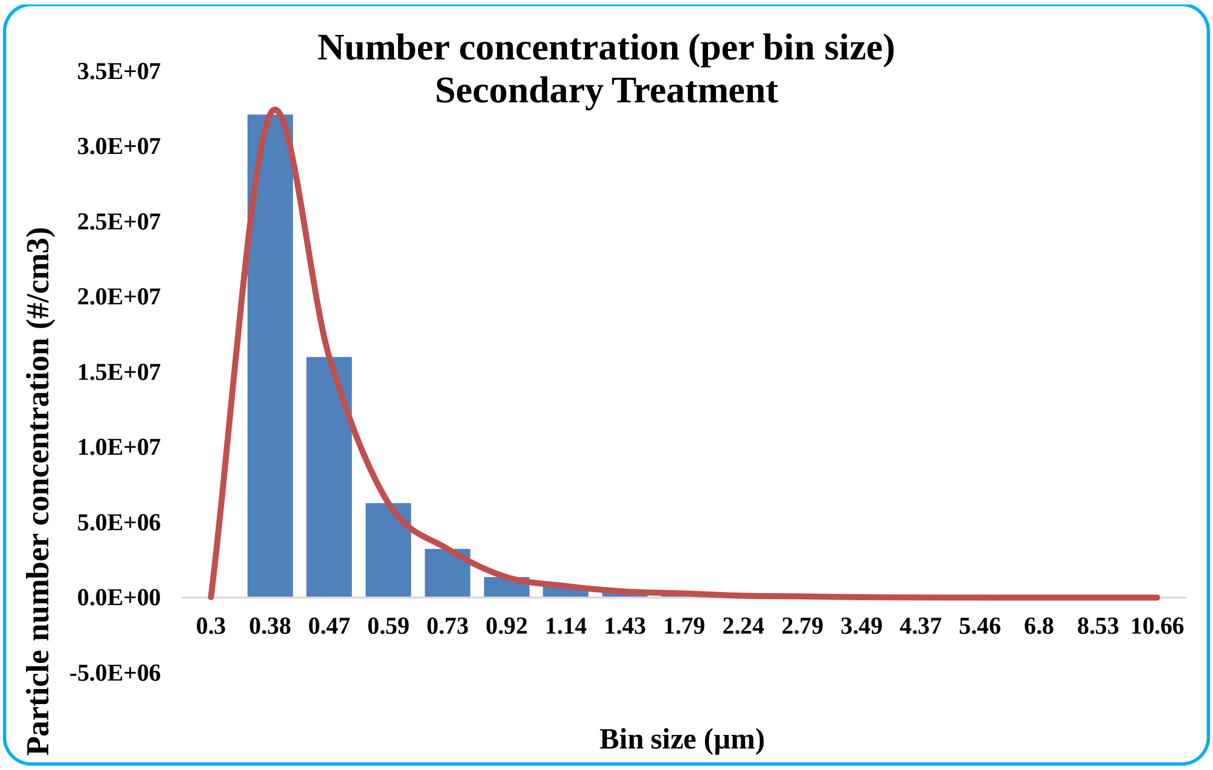

Figure 13: Number concentration per bin size in the Secondary Treatment Area

According to the **Table 2** below an average of 60.7 million (±552879) particles are released over a period of 65 minutes at the total mass concentration of 9.25 µg/m³. Up to 95% of the total number concentration is represented by small submicron particles, accounting for up to 42% of the total mass concentration of all emissions generated at the secondary treatment area. The rest (±5%) falls below the $PM_{2.5}$ bin size range. Almost the entire particle emissions in this area are highly respirable.

Table 2: Mass and Number concentrations per bin size in Secondary Treatment Area

Secondary Treatment				
Bin size (µm)	#/Conc. #/cm3	Mass Conc. µg/m³	% Number contribution	%mass contribution
0.3	3.1E+04	0.0001	0.05	0.00
0.375	3.2E+07	0.97	52.91	10.48
0.468	1.6E+07	0.94	26.35	10.16
0.585	6.3E+06	0.72	10.34	7.77
0.732	3.2E+06	0.73	5.34	7.85
0.915	1.4E+06	0.60	2.24	6.44
1.144	7.7E+05	0.66	1.26	7.09

1.430	4.0E+05	0.68	0.67	7.31
1.788	2.7E+05	0.90	0.45	9.69
2.235	1.2E+05	0.79	0.20	8.51
2.793	7.8E+04	0.97	0.13	10.45
3.492	2.8E+04	0.69	0.05	7.47
4.365	9.5E+03	0.45	0.02	4.90
5.456	1.5E+03	0.14	0.00	1.46
6.821	2.1E+02	0.04	0.00	0.40
8.526	1.0E+00	0.00	0.00	0.00
10.658	1.0E+00	0.00	0.00	0.01
Sum	**6.1E+07**	**9.25**	**100**	**100**

4.3 Results for objective 3: Water bath

Although the water bath exists for the main purpose of cleaning the final product before it is stockpiled and sold to the clients, it also serves a secondary important purpose of reducing dust further after the exposure to the water sprays in the secondary treatment area. The particle number concentration and the mass concentration average of the total dust emissions have been reduced by 75.2% and 97.7% respectively between the primary and tertiary treatment areas. However, the persisting fine PM following suppression is still significant and may possess the potential for inhalation by humans or deposition into the environment.

Figure 14 illustrates the real-time mass concentration of emission over a period of 60 minutes at tertiary treatment area. Despite a very high peak (53.8μg/m^3) in the beginning the emissions are much less in the tertiary treatment area, ranging between 3.4 and 32.5μg/m^3. There are lower peaks compared to the first two treatment area, between 0-10th and 20th to 50th minute. Again, these are due to variation rates of emission based on how much dust stone aggregates were generating.

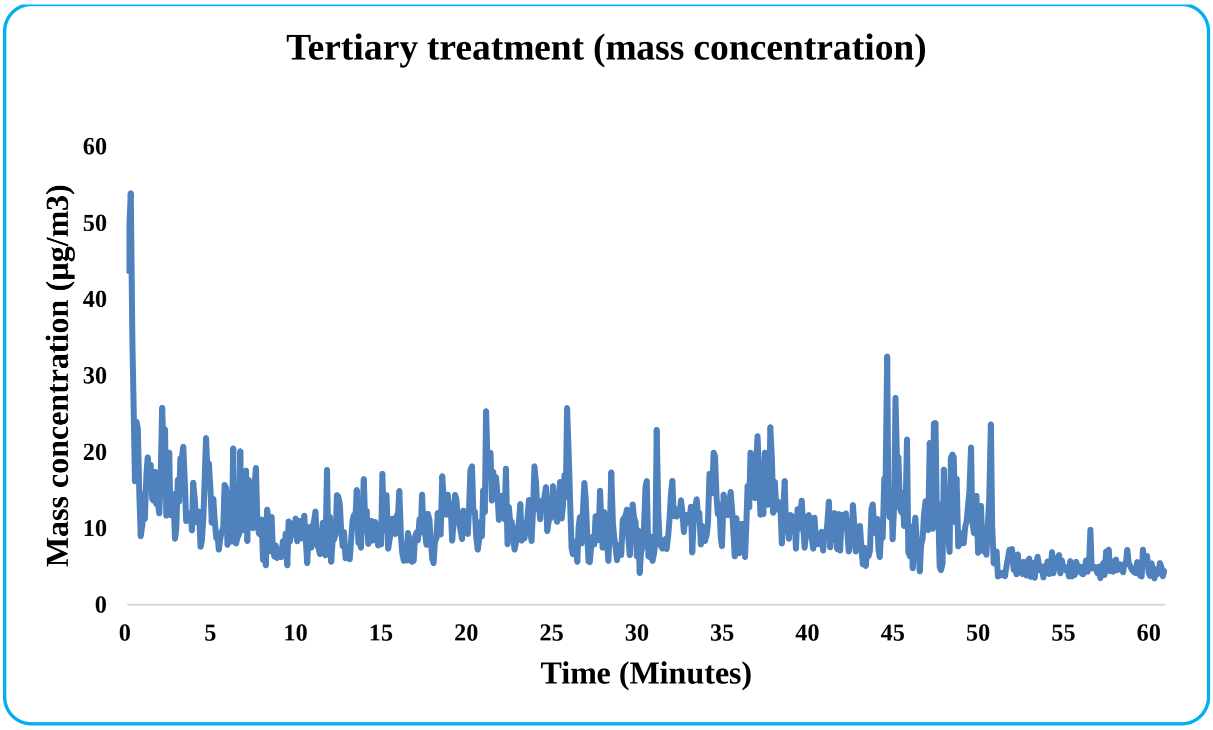

Figure 14: Mass concentration in the Tertiary Treatment Area

The number concentration of dust in tertiary treatment area (**Figure 15**) has greatly declined owing to the reintroduction of the dust emission source (stone aggregates) to large amount of water. However, this does not fully suppress the number concentration as can be observed below. The total number concentration still averages 54.8 million particles per cubic centimeters (±828126), and peaks at 15th to 25th and 35th to 40th minute intervals due to emission variations during transportation of aggregates on the conveyor. The peaks here are no longer consistent with peaks in mass concentration that were observed in **Figure 14**.

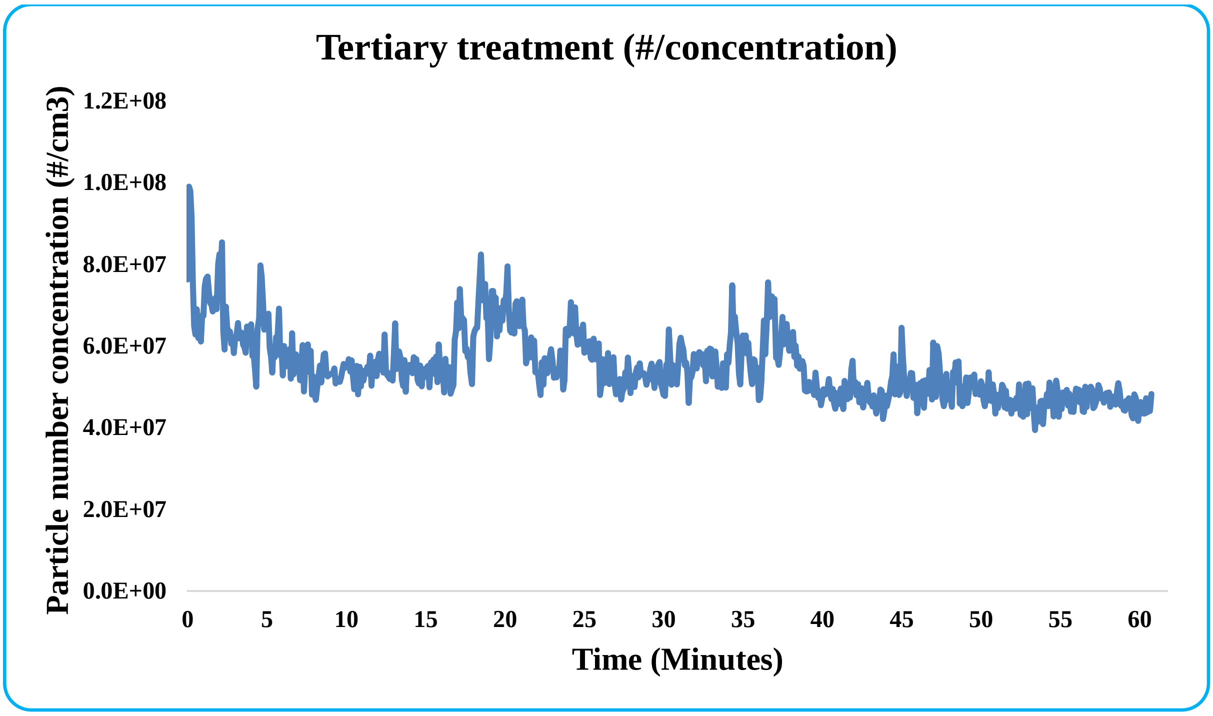

Figure 15: Number concentration in the Tertiary Treatment Area

In **Figure 16**, the distribution of mass concentration per bin size is skewed to the left with the larger particle size bins occupying most of the mass concentration. The submicron particles count for a smaller portion of the total mass concentration. The $PM_{2.5}$ – PM_4 particle range accounts for almost 50% of the total mass concentration because the larger particles are heavier in terms of mass and also possibly due to binding of water molecules.

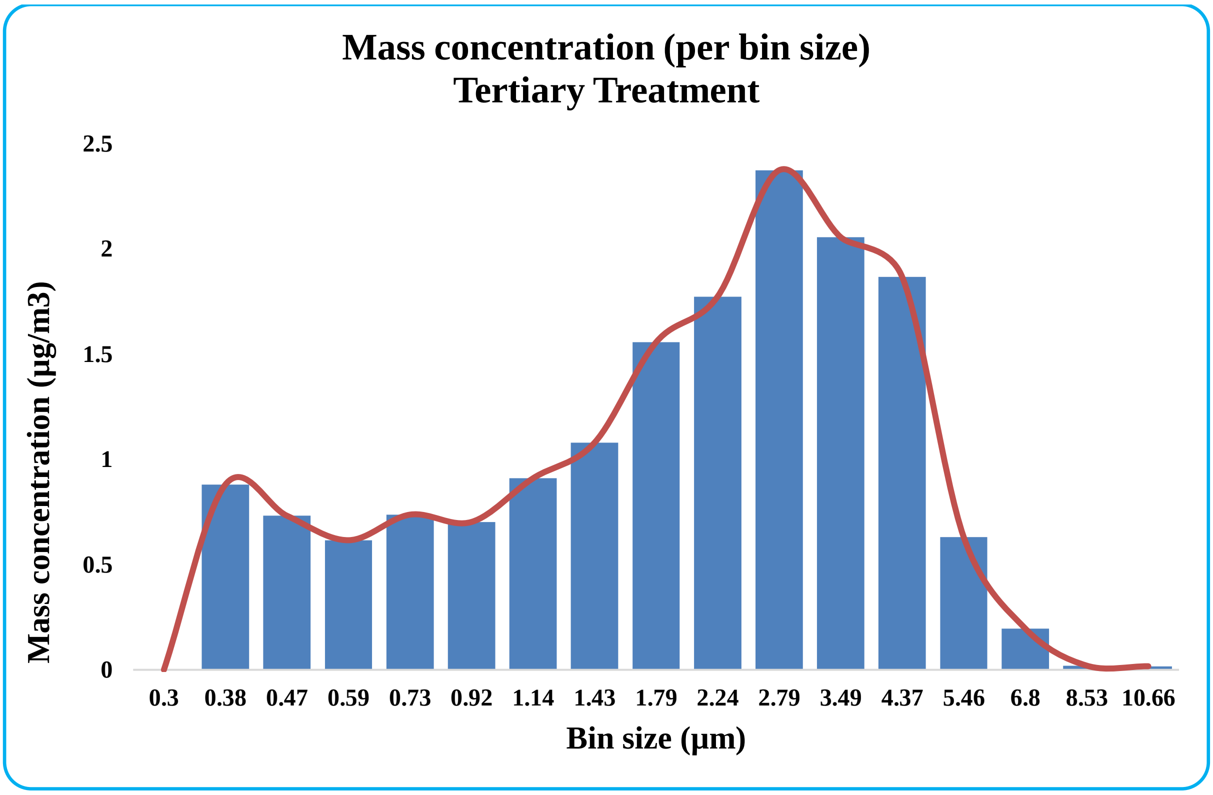

Figure 16: Mass concentration per bin size in the Tertiary Treatment Area

Despite the exposure of stone aggregates to the bath full of water, the data shows that its impact on the fine particles below 0.4 microns is still very insignificant. This is demonstrated by only a 9% reduction of the 0.4micron particles from the particle number concentration in the secondary treatment area. As particle size bin and particle diameter increases there seems to be more reduction in the number concentration due to exposure to pooled water. The results in **Figure 17** is therefore skewed to the right as a result, supporting the theory that water has less impact on smaller particles, mostly in the lower submicron range.

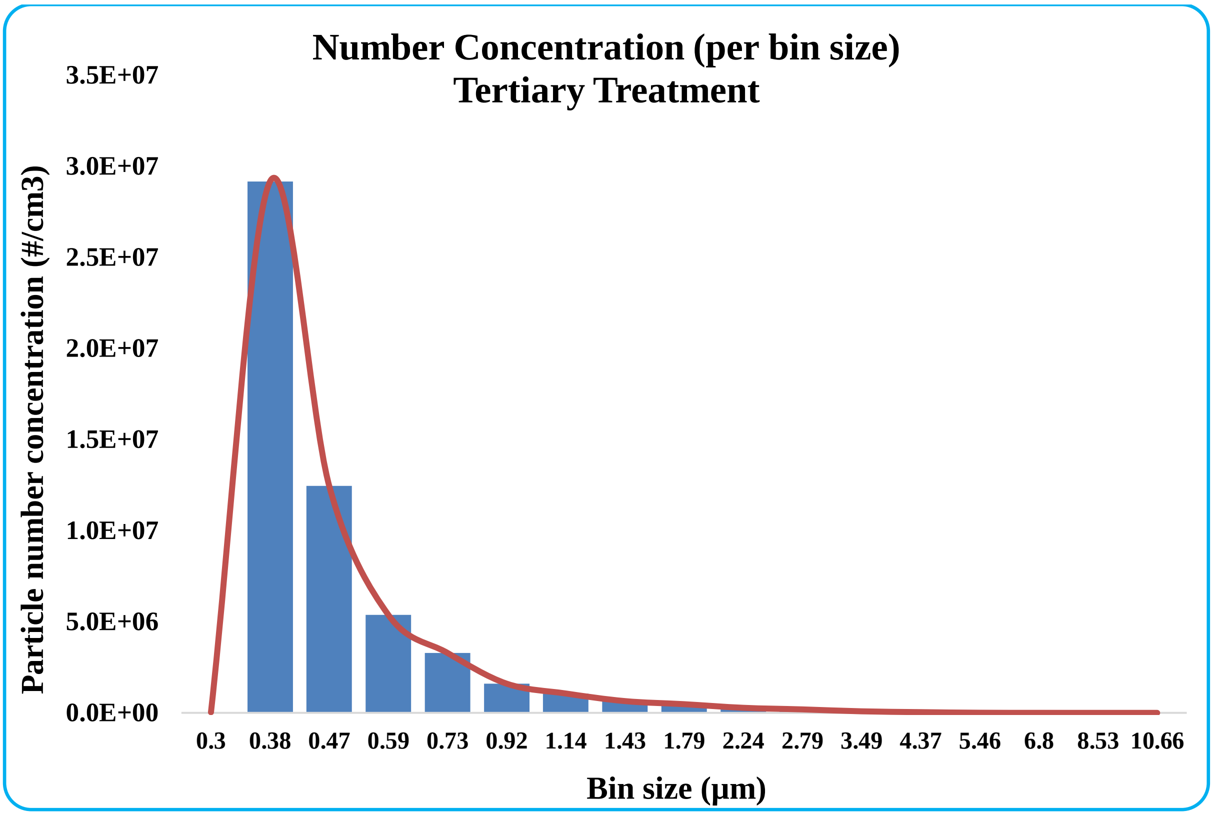

Figure 17: Number concentration per bin size in the Tertiary Treatment Area

The mass and number concentration table (**Table 3**) below demonstrates that 95% of particles emitted in tertiary treatment area falls within the submicron range, with over 53% accounted for by particles smaller than 0.4 microns. The mass concentration particle size distribution is skewed to the left and therefore the larger particles account for over half of the total mass concentration despite being in very small quantities compared to submicron particles. The total average number concentration of tertiary treatment as per **Table 3** is 54.7 million per cubic centimetres (±828126) with the total calculated weight of 16.15µg/m^3.

Table 3: Mass and Number concentrations per bin size in Tertiary Treatment Area

Bin size (µm)	#/Conc.	Mass Conc.	% Number contribution	%mass contribution
	#/cm3	µg/m^3		
0.3	3.28E+04	0.0001	0.06	0.00
0.375	2.92E+07	0.88	53.32	5.45
0.468	1.25E+07	0.73	22.76	4.53
0.585	5.38E+06	0.62	9.83	3.81
0.732	3.29E+06	0.74	6.01	4.57

0.915	1.60E+06	0.70	2.93	4.35
1.144	1.06E+06	0.91	1.94	5.64
1.430	6.45E+05	1.08	1.18	6.68
1.788	4.76E+05	1.56	0.87	9.64
2.235	2.78E+05	1.77	0.51	10.98
2.793	1.90E+05	2.37	0.35	14.70
3.492	8.44E+04	2.06	0.15	12.73
4.365	3.92E+04	1.87	0.07	11.56
5.456	6.79E+03	0.63	0.01	3.91
6.821	1.08E+03	0.20	0.00	1.22
8.526	5.56E+01	0.02	0.00	0.12
10.658	2.44E+01	0.02	0.00	0.10
Sum	**5.5E+07**	**16.15**	**100**	**100**

4.4 Results for sampling area 4: Emission levels around the office block

From our observations data shows that $PM_{2.5}$ particles are able to travel some 200m from the source down to the office complex. The wind conditions were normal and could not have had a significant influence on the movement of the particles on the day. Mass concentration recordings in **Figure 18** show a gradual decline from the first three monitoring areas, with peaks on the 51st, 58th, and 60th minutes. Although the mass concentration levels and average are very low, the particles were still able to travel to the offices where employees and few animals and plants species exist.

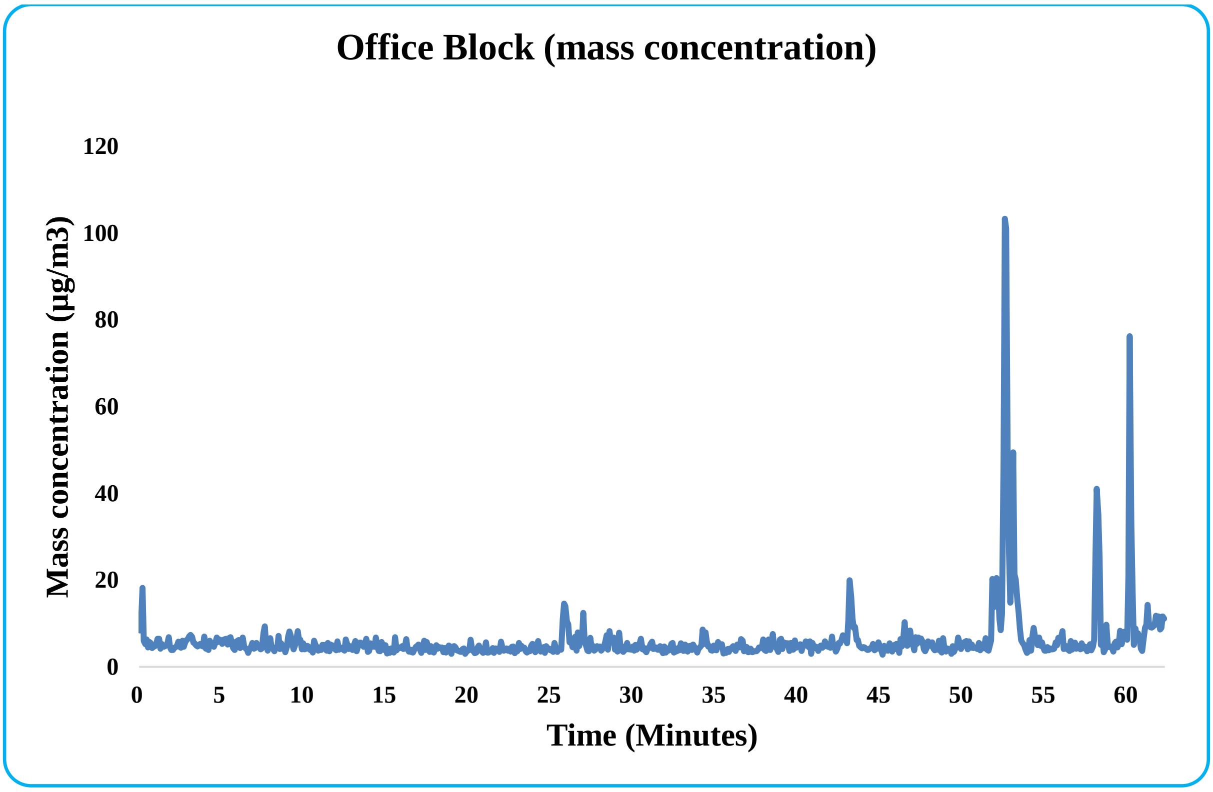

Figure 18: Mass concentration in the Office Block

Measurements around the office block were taken as control to determine if the dispersion of PM from the source (activity area) to the office block is possible and to determine possible emissions profiles around the offices. The number concentration results in **Figure 19** is very consistent with the mass concentration, peaking at the exact points. The number concentration levels are also very low in this sampling environment compared to the activity areas (Figure 9, Figure 11 and Figure 15) and average at approximately 44.4 million particles per cubic centimeters.

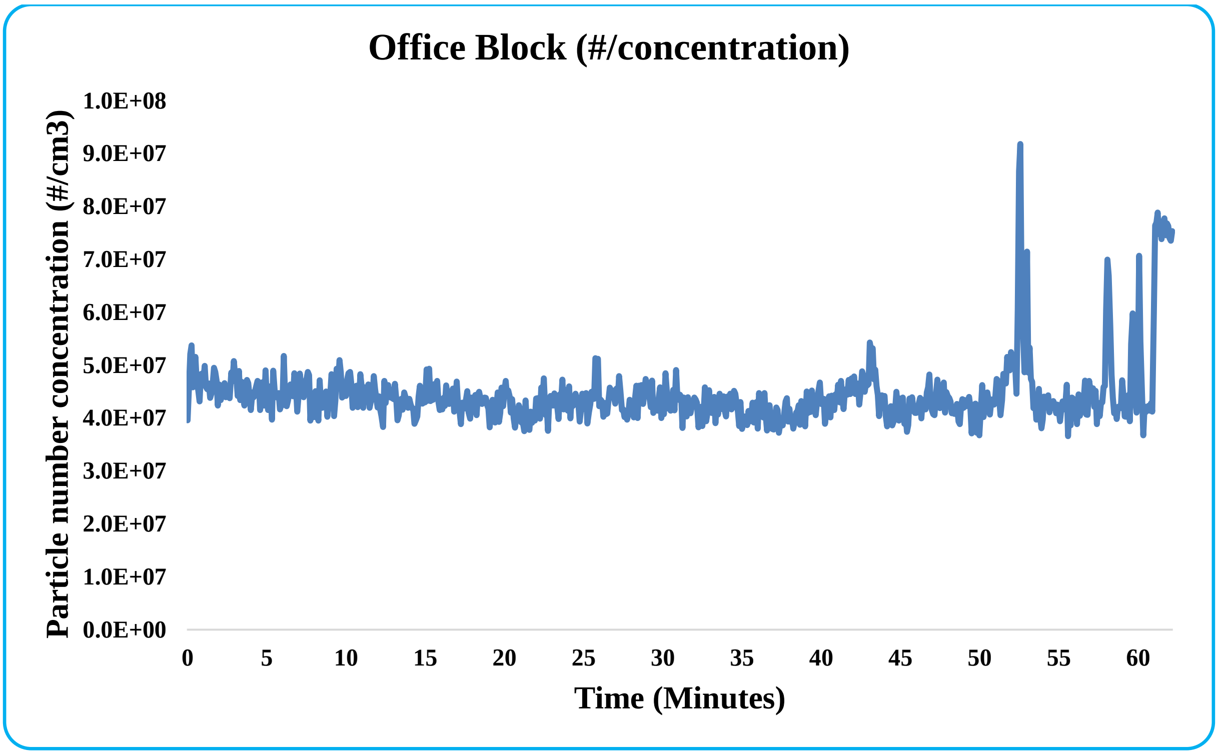

Figure 19: Number concentration in the Office Block

In **Figure 20**, it can be observed that larger particle bins account for most of the total mass concentration of emissions around the office block. The submicron particle in various size bins accounts for 28.1, while larger particles accounted 38.9% of the total mass, and collectively with the $PM_{1.0}$ to $PM_{2.5}$ size range make up to 86.6% of the total particle mass concentration. Although it is hypothesized that due to the size and weight of the larger particles it is unlikely that they will travel so far up to the office block, there is possibility of resuspension of larger deposited dust particles not far from the office block to contribute to the measured levels.

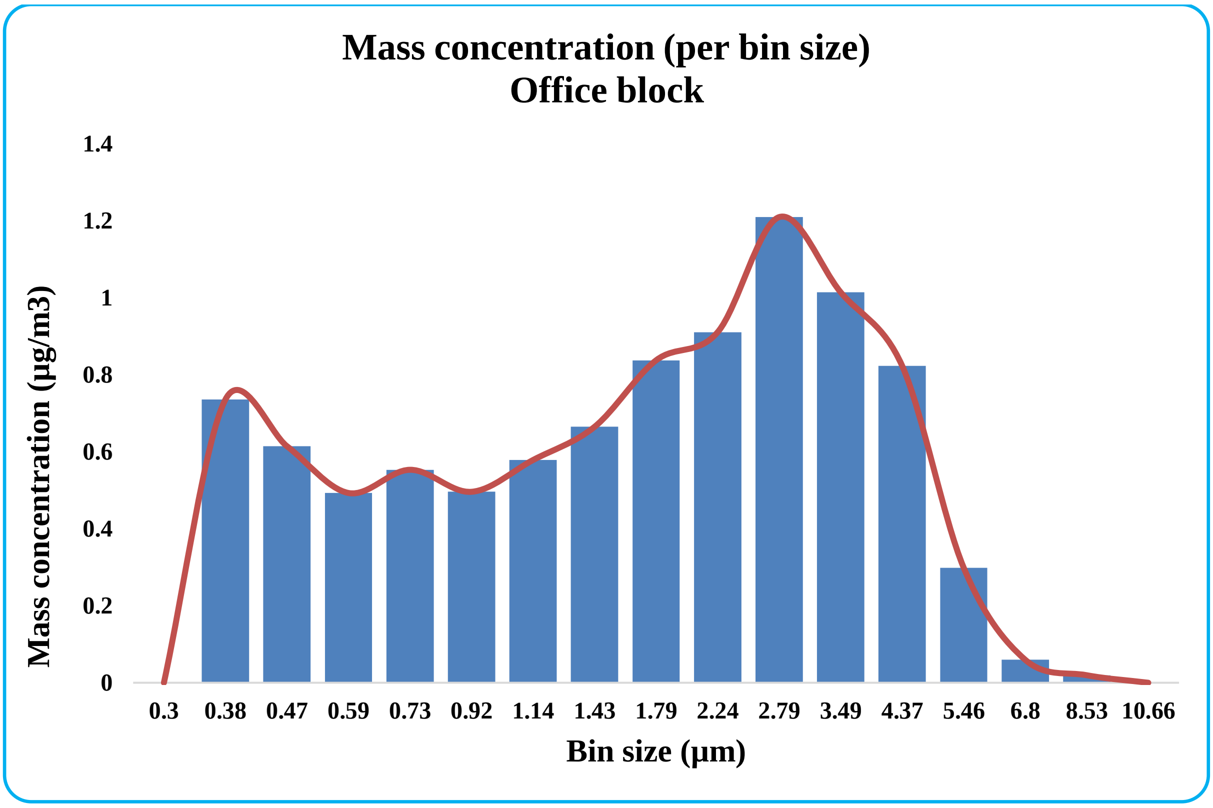

Figure 20: Mass concentration per bin size in the Office Block

The particle size distribution in the Office Block (**Figure 21**) is consistent with the emission levels from the secondary and treatment areas and this demonstrates that dust particles collected around the office complex originated from the crushing plant. The particle concentration data is skewed to the right, similarly to the last two sampling points. There is predominance of submicron bin sizes, accounting for a total of 96%, and over 99% of particles detected at the office block falls within the sub-$PM_{2.5}$ range. Possible origins are the hauling roads around the office building complex and various stockpiles around the crushing plant.

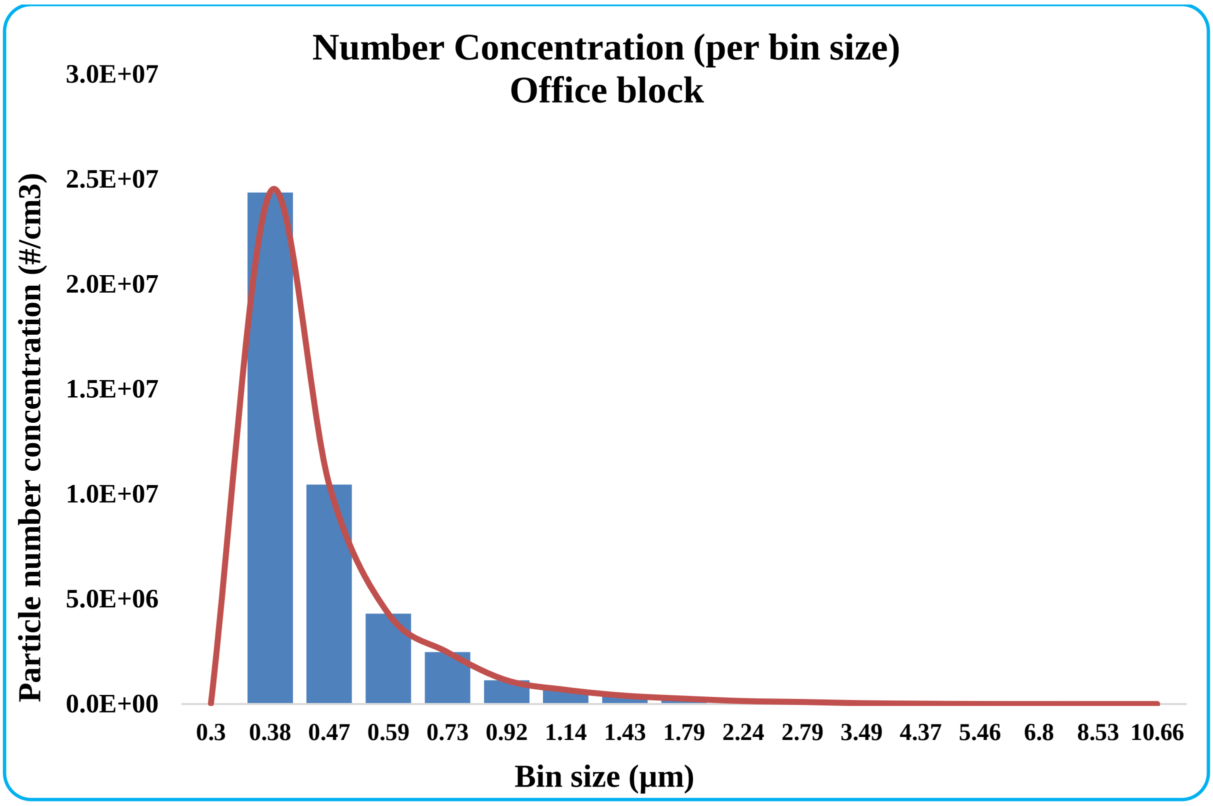

Figure 21: Number concentration per bin size in the Office Block

The results displayed in **Table 4** illustrate the average total particle number concentration of 44.4 million particles per cubic centimetre (±628078) with a total calculated mass concentration of 10.3 µg/m^3. These concentrations are below the other samples collected at different treatment areas and are possibly affected by various mechanical and environmental effects such as meteorological conditions.

Table 4: Mass and Number concentrations per bin size in Office Complex

Bin size (µm)	#/Conc.	Mass Conc.	% Number contribution	%mass contribution
	#/cm3	µg/m³		
0.3	2.45E+04	0.0001	0.06	0.00
0.375	2.44E+07	0.74	54.92	7.14
0.468	1.05E+07	0.61	23.55	5.96
0.585	4.30E+06	0.49	9.69	4.78
0.732	2.47E+06	0.55	5.56	5.37
0.915	1.13E+06	0.50	2.55	4.81
1.144	6.75E+05	0.58	1.52	5.61
1.430	3.97E+05	0.66	0.90	6.45
1.788	2.56E+05	0.84	0.58	8.12
2.235	1.43E+05	0.91	0.32	8.83

2.793	9.70E+04	1.21	0.22	11.73
3.492	4.16E+04	1.01	0.09	9.84
4.365	1.73E+04	0.82	0.04	7.98
5.456	3.21E+03	0.30	0.01	2.90
6.821	3.28E+02	0.06	0.00	0.58
8.526	5.50E+01	0.02	0.00	0.19
10.658	0.00E+00	1.00	0.00	9.70
Sum	**4.4E+07**	**10.31**	**100**	**100**

4.5 Results for objectives 4 and 5: Comparison of mass and number concentrations and efficacy of WSM against submicron particles.

Figure 22 compares real-time mass concentrations at different sites over a period of 60 to 70 minutes. It can be demonstrated that the mass concentration of the dry treatment site before any water suppression shows a very high emission concentration compared to the wet treatment areas and the control area. The mass concentrations of emissions at the rest of the sampling size are drastically reduced, demonstrating the capability of water suppression method to suppress fugitive dust as a control mechanism in the workplace.

In terms of mass concentration, it can be evidently observed that there is a massive decline in emissions following water suppression and that the portion of dust emissions that is able to reach the office block is very small compared to original dust emissions at the primary treatment area.

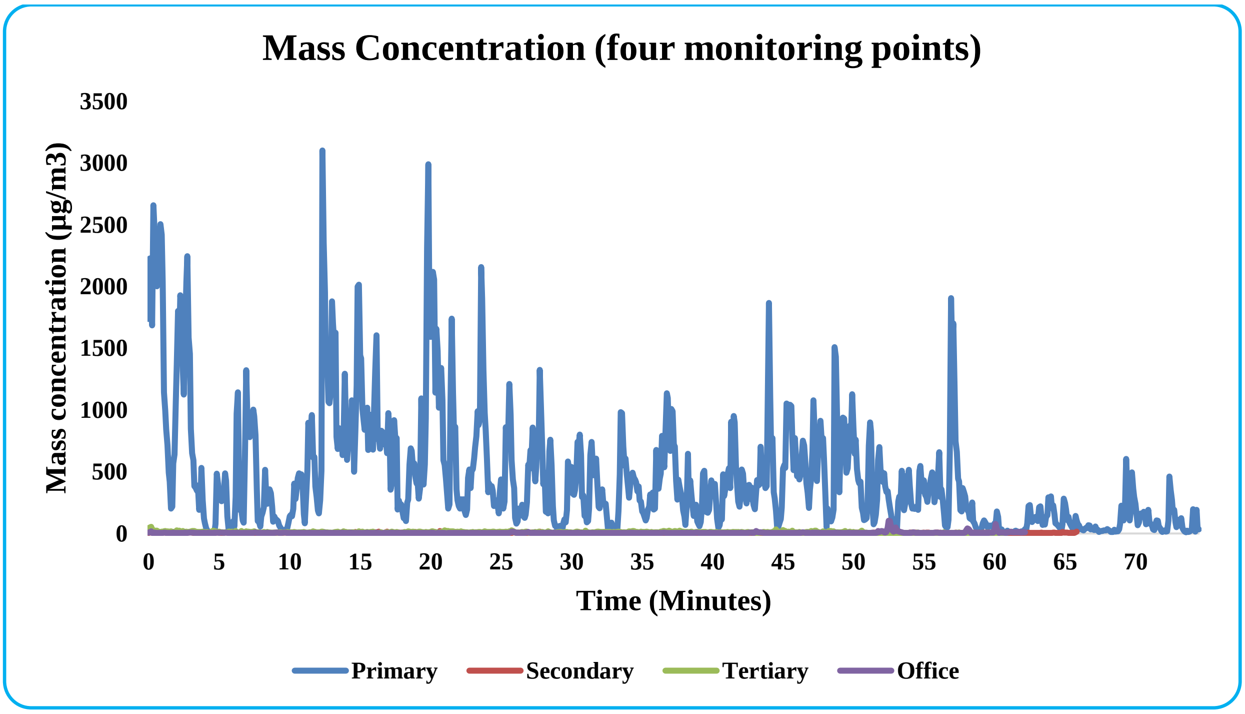

Figure 22: Mass concentrations at 4 sampling locations

The average mass concentrations of different monitoring sites are demonstrated in **Figure 23**. It can be observed that large mass concentration amounts of dust emitted from the primary treatment area (460.2µg/m^3) exceeding the Occupational Exposure Limit (0.46mg/m^3 > 0.1mg/m^3) have been significantly reduced by 98.7% in secondary treatment phase, and 97.7% in tertiary treatment phase respectively. However, it has also been demonstrated that the high mass concentration in the primary area mostly consists of large dust particles whereas at the rest of the sampling sites it consists of smaller particles and a combination of both. Data has also showed that in terms of the bin sizes only the larger ones are highly suppressed by wet suppression methods whereas the smaller bin sizes are not equally suppressed. These smaller particles contribute noticeably to the remaining mass concentrations at the three latter sampling sites despite water suppression.

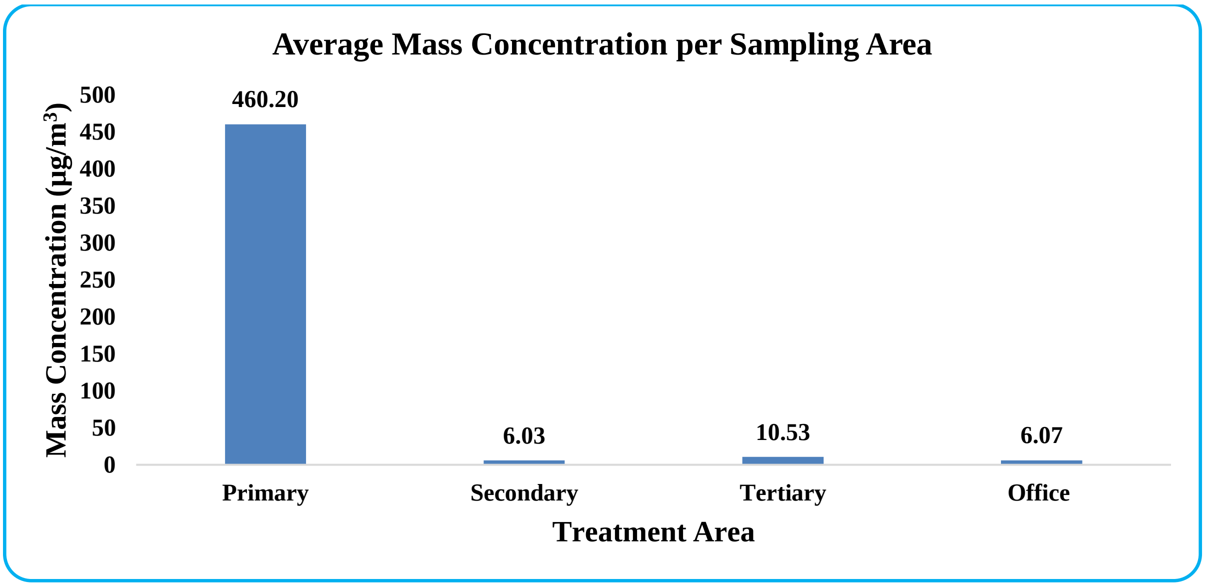

Figure 23: Average mass concentrations at different sampling areas

Figure 24 demonstrates the comparison of real-time number concentrations at different treatment areas and sampling points. It can be shown that a there is a much higher particle number concentration in the primary area, where there is no water suppression, followed by the secondary, tertiary treatment area, and the office block respectively. This means that in terms of the reduction of total number concentration across different bin sizes the water suppression appears to be effective.

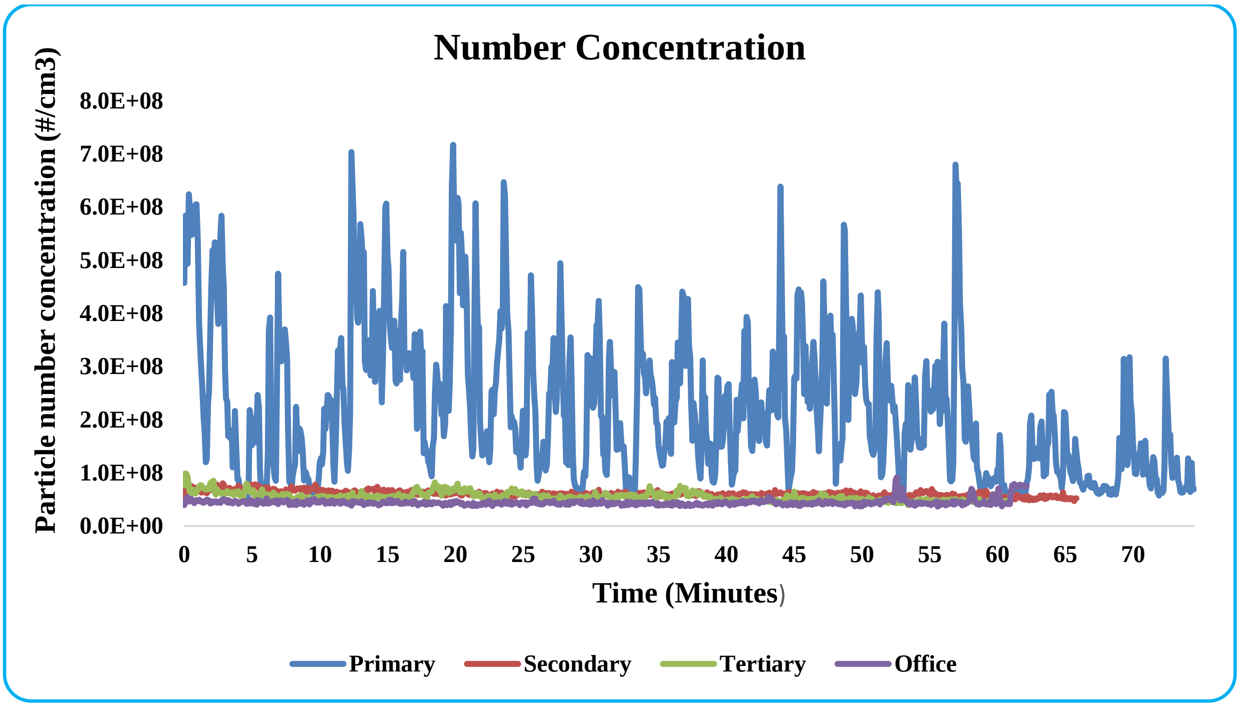

Figure 24: Particle number concentrations in all sampling locations

Furthermore, **Figure 25** illustrates the average number concentration across all bin sizes decreases at different sizes after water suppression has been applied, and at the control site where dust particles that have possibly been transferred from the source to the potential receptor location. It shows a decline in average concentrations by 3.65 folds between primary and secondary area, 4.05 folds between primary and tertiary areas, and 4.99 folds between primary area and the office complex.

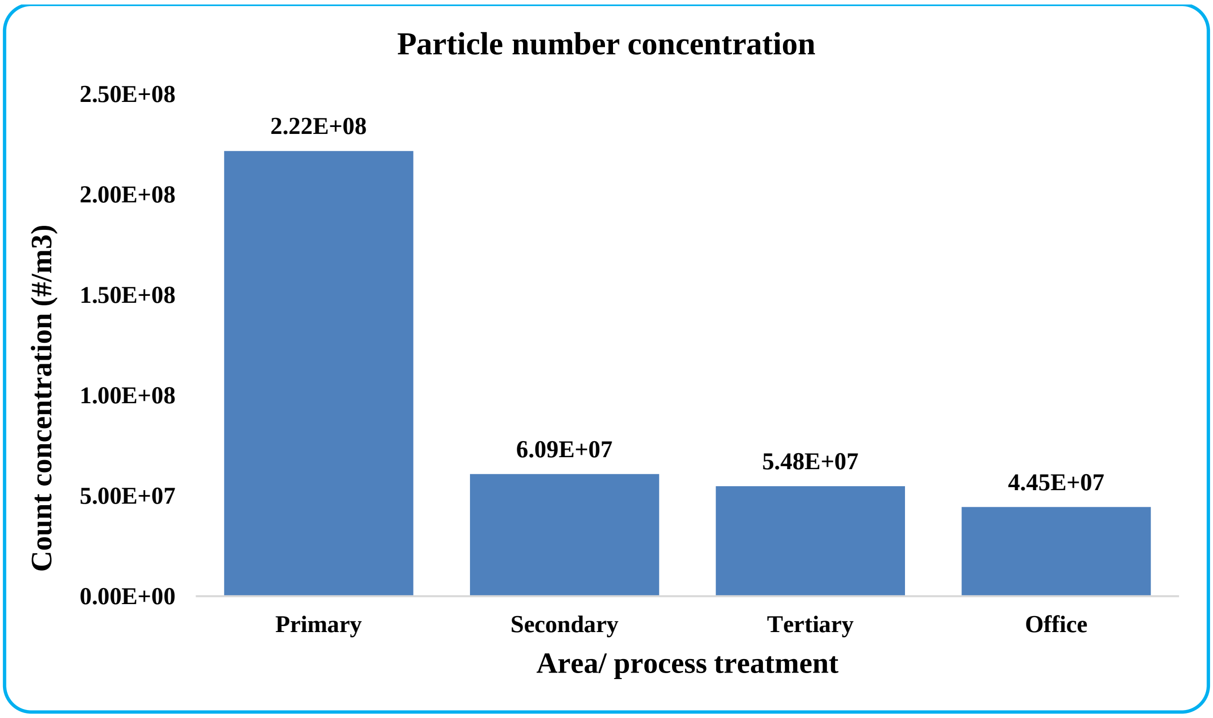

Figure 25: Average total number concentrations at different sites.

Table 5 summarizes number concentrations and mass concentrations across different treatment areas. It can be demonstrated that both mass concentration and number concentration are reduced at different rates across different treatment sites. The primary treatment area is used as a baseline where there is no water suppression to demonstrate the impact of water suppression applied at subsequent monitoring sites and the office complex (control site).

Table 5: Average number and mass concentrations

Process	**Number concentration #/cm^3**	**Reduction factor**	**Reduction %**	**Mass concentration (µg/m^3)**	**Reduction factor**	**Reduction %**
Primary	2.22E+^{08} (±129827)			460.20		
Secondary	6.09E+^{07} (±552879)	3.64	73%	6.03	76.36	99%
Tertiary	5.48E+^{07} (±828126)	4.04	75%	10.53	43.71	98%
Office	4.45E+^{07} (±628078)	4.99	80%	6.07	75.85	99%

Finally, in order to fulfil the main objective of our study which is to determine the effect of WSM against submicron particles, we have further broken down the submicron data in **Figure 26.** The study has demonstrated that most suppression occurs in the larger particle bin size range and thereby affecting the mass concentration more than it does number concentration. The residual PM in the wet treatment areas and the office block mostly consists of smaller submicron particles. The data in **Figure 26** demonstrates that the average number concentrations in within the submicron range are only reduced by 2.2 times between primary and secondary areas, 2.5 between primary and tertiary areas, and 3.04 between primary treatment area and the office block. These reductions are not consistent with the reductions in mass concentrations outlined above, and therefore the effectiveness of this method appears to be less within the smaller particle bin size range (submicron).

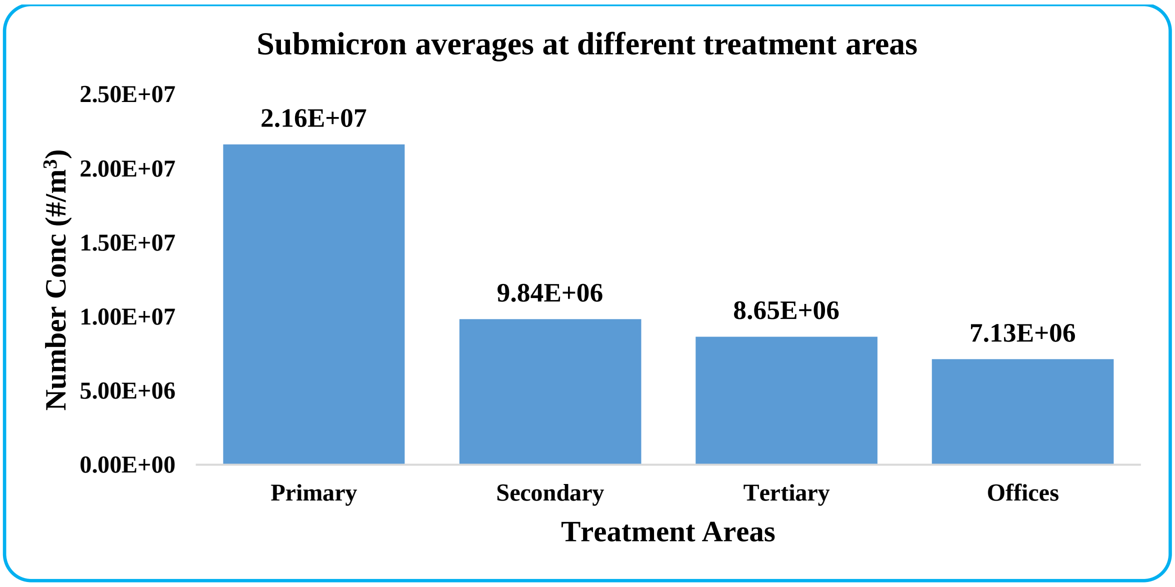

Figure 26: Submicron particle number concentrations at different treatment areas

Figure 27below further demonstrates that the smaller the particle diameter the less the impact of water suppression. In this illustration the 0.375um particles are less suppressed by the wet interventions compared to larger particle bin sizes within the submicron range. It is also shown that the same bin size is emitted in much higher number concentrations compared to the larger bins on which water suppression appears to have a better effect. This means that smaller particles continue to linger in the air for much longer around and away from the emission source after the WSM has failed to significantly reduce their number concentrations and are available to become source of exposure within the occupational and environmental settings.

Human exposure to these particles could lead to health effects as described in Chapter 2. This further demonstrates that despite the absence of emission sources around the office complex almost half the concentration of the primary treatment area 0.375µm bin size particle emissions are able to remain in the air long enough to reach the office complex.

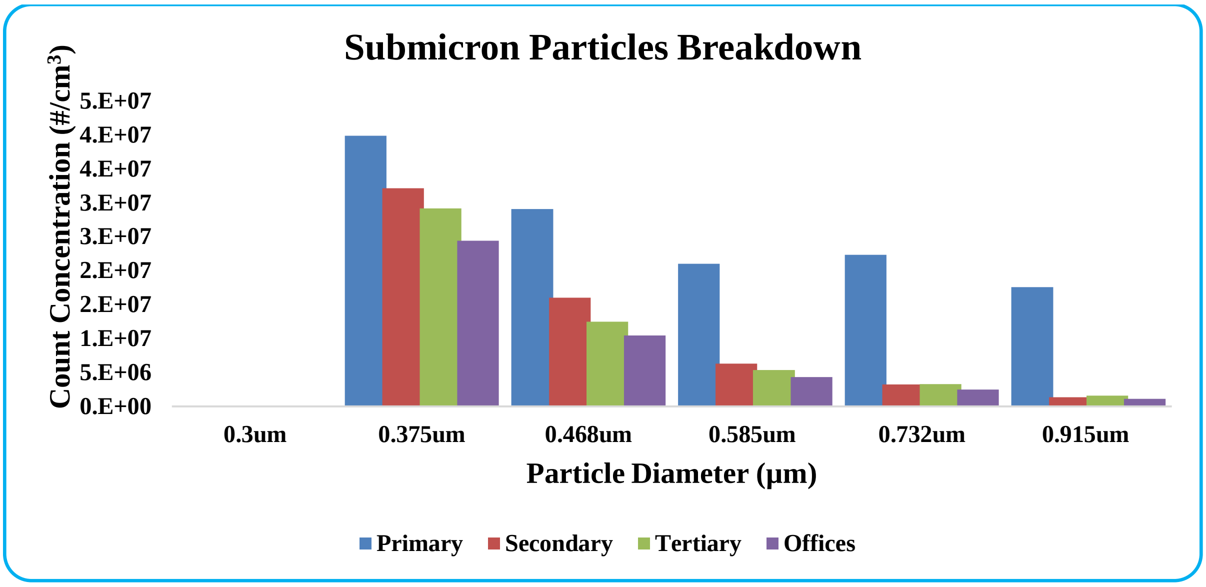

Figure 27: Submicron particle number concentration reduction at different sites

5. CHAPTER FIVE

This chapter begins with the discussion of results and conclusions drawn from the findings. It also describes various limitations and strengths that are associated with the study of its nature, and future research opportunities that can be derived from this study or data, or any other aspect of this and related studies. Finally, recommendations are made on how to ensure safe quarries and stone crushing plants as the primary means of maintaining a healthy and safe working environment for workers and neighbouring communities and nature.

5.1 Discussion & Conclusions

The results showed that large amounts of different particle sizes are emitted during primary treatment phase. This is demonstrated by high particle mass and number concentrations for PM in different bin size ranges. Between the primary and secondary treatment areas, after water suppression has been introduced, the mass concentration and number concentration of the large particle bin sizes begin to drop, and the fine particles becomes predominant at the secondary treatment area, with a shift of data distribution to the right due to smaller particle bin sizes accounting for a higher portion of the total number concentration. This is due to two possible reasons as reported in literature, 1) particulate matter deposition near the source due to larger particle diameter and mass, and 2) reduction in mass and number concentration by the water suppression applied during secondary treatment.

This study demonstrates that water suppression is effective against the total dust emissions by reducing the total mass concentration by 98.7% between the primary and secondary treatment areas. The total number concentration was also reduced by 72.5% from the average of $2.22E+^{08}$ $/cm^3$ to $6.09E+^{07}/cm^3$ due to the application of water suppression. This is consistent with studies that suggest that water suppression reduces dust emissions, even though it may be for a short period due to quick evaporation [21,23]. Based on the results obtained at the secondary and tertiary treatment areas as compared to the primary area it has been demonstrated that the number concentration of $PM_{2.5}$ and larger particle bin sizes forms a major portion of the dust concentration suppressed by application of water, while the total mass and number concentrations of particle size bins smaller than 2.5 microns appear to be reduced only to a lesser extent. The residual 27% of total dust concentration after the application water suppression treatment in the secondary treatment area consists mainly of PM smaller than 2.5 micron, with particle number concentrations increasing with the decreasing particle diameter. At this level, data clearly demonstrates that although water suppression has positive reduction effect on the total mass concentration of dust emissions, this is mostly effective against larger particles and to a much less degree on the smaller particle bin size range.

Although the entire submicron particle range appears to be less affected by the water treatment, the particle diameter range that remains in very high concentrations following exposure to water treatment is the sub-0.5 micron range. This is the particle bin size range that has been demonstrated (Figure 3) to penetrate the smallest airways of the lungs and cause adverse health effects such as silicosis.

Following water treatment, the average mass concentration of PM at the second sampling point over 8 hours (TWA-8) is 0.05mg/m^3, half of the acceptable occupational exposure limit after water treatment. Although this exposure concentration is acceptable according to regulations the level of submicron PM that has not been affected by water suppression remains high and needs to inspire new and different approaches in dust control measures.

The submersion of stone aggregates into the water bath should provide a potentially more effective form of water suppression compared to the sprinkler system and has also been shown to be responsible for a further decrease in the number concentration of PM_4 and larger particles. However, there is predominance of the high mass concentration levels accounting for more than 50% within the larger particle bin sizes despite drastically reduced number concentrations in the same bin size range. This could be due to the binding of small particles to water molecules thereby increasing the bin size as suggested by Lee in 2019. It has also been demonstrated that water suppression is not as effective on smaller submicron particle bin size range compared to larger particle sizes, especially below the 0.4 micron bin size range as demonstrated in Figure 17 and Figure 27. PM reduction pattern in terms of number concentration consistent with the first water suppression method (sprinkler) was also shown by the water immersion system. In this process, similar to the sprinkler system in secondary treatment, the effectiveness of immersion evidently increased with the increasing particle size diameter as observed in the water sprinkler method.

The results conclusively demonstrate again that water suppression is more effective against large dust particles and has a lesser effect on the submicron bin size range. There is only a 12% reduction of the average number concentration of submicron particles between sampling points in secondary and tertiary treatment areas. This could be best explained by two possible processes: 1) the dust emissions of the aggregates before the submersion prevails around the area and a large portion thereof is captured by the sampling tool after the submersion, or 2) during the submersion water molecules fail to adhere to the submicron particles for long and as soon as the aggregates emerge out of the bath and physically collide against each other while on the conveyor they continue to emit submicron particles which are not fully arrested by the water molecules.

The results also shows that particle diameter range below the 0.5-micron size make up most of the bulk of the dust emissions at the secondary and tertiary treatment areas, particularly the 0.375µm range. This particulate matter size range continue to prevail in the vicinity of the source and is potentially able to travel over 200m to the office complex where it can be inhaled by the unprotected workers, this is consistent with findings from the other published study (Bluvshstein, 2011). Although the concentration of these particles that have failed to be arrested at the source level remain relatively lower than the 8-hour OEL, the cumulative and aggregate exposure over a longer period of time could still lead to adverse health effects in the workers or nearby communities.

The measurements of PM that have been obtained at the office block, some 200m away from the source demonstrate that normal quarry dust control mechanisms are not fully effective against the entire particle size range, and this presents a new challenge to closely look into the control of submicron dust particles in order to study their potential impact on human health and possible control mechanisms. Bluvshstein et al. has demonstrated that particles are able to move as far as over 1 kilometre away from the source depending on wind speed and direction [34]. In studies by du Plessis and Lee it was also demonstrated that addition of lignosulphonate and PEG respectively were able to increase the effectiveness of water suppression [21,23] and this, together with other potential water additives, could be tested against smaller particles.

Emissions of larger particles is evidently easily and adequately controlled by current dust control mechanisms in terms of both mass and number concentration, assisted by the process of large particle deposition around the source due to the particle size weight consistent. This finding is similar to those reported in studies by Sairanen and Bluvshstein studies. Smaller particles appear to remain in the air for much longer where the dispersion and movement could be influenced by wind direction and speed as described in literature. In some studies wind was shown to be able to transport PM to as far as 350m away from the source [36,102], facilitated by weather conditions (wind direction and speed). Resuspension of deposited large particles from nearby stockpiles or the ground could also be responsible for precipitation of large bin sizes (PM_4 – PM_{10}) in the office block sample, and this could also be exacerbated by meteorological conditions such as windiness and low humidity (particles become dry and lighter in weight).

Furthermore, the findings of this study are consistent with other studies in proving that water suppression is mostly effective against larger particles and to a very less extent submicron particles. Many studies that have proven water suppression as a very effective dust control mechanism may not have focussed on its limitations in controlling smaller particles and have not paid more attention on the effects of this submicron group on human health and the environment. This presents a unique new challenge for researchers and technology to continue to innovate advancements to be able to address such problems and enable ways to come up with solutions based on problems that will be identified.

Since the focus on learning the behaviour and impact of submicron and ultrafine particles on human health and the environment in general is still relatively not advanced. It has been overlooked for a long time due to reasons such as limitations in capabilities of measuring equipment and little understanding of aerosol physics in most part of the developing world. Researchers are presented with a new challenge of reassessing what is known and how estimations have been applied in certain exposure control mechanisms and theories to incorporate the new body of knowledge and understanding that are brought on through development of new technologies and their capabilities.

The fact that researchers may not know and understand the full effects of prolonged exposure to fine PM and UFP could present new opportunities to uncover associated problems that we may not have been able to identify in the past. It has also been suggested that for smaller particles number concentration should be used as a measure to quantify exposure rather than mass concentration. This may help researchers and legislative bodies to set new exposure limits consistent with the behaviour of known dust control mechanisms against submicron particles and their efficacy. This is very crucial as we have demonstrated that despite a large decline in total average and calculated mass concentrations due to water suppression across large particle bin size range, the effect is very much less within the smaller submicron range, even more so below the 0.4 micron range.

The available literature does not demonstrate that adequate dust control mechanisms are targeted at this size range despite its devastating potential health effects, and this raises suspicion that the current regulatory guidelines do not fully protect workers and communities against this very dangerous health hazard. Determining toxicity through mass concentration only could only provide partial insight into a very complex problem that requires consideration of number concentration as a very important indicator of exposure risk and toxicity.

5.2 Study Limitations

The measuring instrument cannot differentiate between aerosols and dust particles due to its ability to measure particles based on their size. Microdroplets of water where water suppression was applied may have been counted as dust particles. However, due to the consistency of the data across different sampling stations this may have had little to no effect on the study findings. Enough sampling time was allocated to ensure accuracy of results and reduce uncertainty.

The measuring device (Nanozen) does not have ability to separate dust particles originating from our source of interest and from the background dust from other sources in the area such as haulage roads and stockpiles. Dust that could have been blown to the plant from far field location could also be counted and influence the results. However, on the day of sampling the wind was minimal, and this could only have had a minor effect if any at all. There are residential areas in <1 kilometer from the quarry and the emissions could end up being transported to the quarry through wind if proper control measures are not instituted. The mining site is also in the vicinity and its emissions could also contaminate the data collected from the processing area.

Emissions could have also been underestimated if wind was blowing in the direction away from the sampling tool towards the source. Wind direction and speed have been demonstrated to have a great impact on the dispersion patterns of PM in many studies [34,94,103]. Placing the sampling tube on one side of the source could underestimate PM emissions if wind is blowing away from the device and overestimate when the wind is blowing towards the sampling device. Again, this was unlikely due to favourable weather and wind conditions during the sampling time.

Resuspension of settled dust or dust from the stockpiles could also be recounted and overestimate the number concentration of PM. The conveyor belts used to deliver aggregates into stockpiles are very close to the stockpile areas and could easily be reached by dust originating from these potential sources.

Variations of emissions based on conveyor belt speed and weather conditions were not taken into consideration during data sampling and analysis. It has been proven in many studies that emissions depend on meteorological conditions such as wind speed and direction and also seasonal variations. Different results could be obtained under different conditions and seasons.

The Level of Detection (LoD) for the measuring device could also affect the results. In our study however, there seemed to be a minimum detection limit of 300µm, and this is highly likely due to the physical characteristics of the PM emitted and the mechanism of dust release. We believe that under different scenarios with different PM materials such as burning fuel emissions a much lower LoD could be achieved.

5.3 Study Strengths

The study successfully managed to measure fine PM that has often been difficult to measure in the past using common tools that were available at the time. The measuring tool made it possible to measure dust in different sizes, up to as small as 300µm and determine the ability of these small particles to be controlled using the most common suppression method that is available to the mining sector. This creates new interest and focus on submicron particle research and affords researchers an opportunity to inform governments and change legislative requirements, thereby improving health and safety of workers and communities living nearby emission sources.

The study was able to achieve very significant findings and draw important conclusions in a subject matter that is difficult to research. A simple personal monitoring device was repurposed for this study and was able to meet expectations in terms of conclusive findings at a very low cost and very short time of analysis and reporting.

5.4 Future Research

Future studies focusing on dispersion patterns of submicron particles have been made possible by this study in which the transportation patterns can be studied, and controls implemented to protect receptors in a far field exposure scenario from the emission sources. It is also possible to perform studies using similar tools to determine the effectiveness of personal protective equipment against submicron particles and inform the development and improvement of such exposure control tools. Due to the newly developed interest in fine particulate matter emissions and behaviour there is a need to determine if workers are indeed protected from this specific hazard that has not really enjoyed attention for a long time.

Finally, new control measures or strengthening of current measures are needed to effectively manage exposure to fine and ultrafine particles. New research is required to drive this initiative and ensure that omission of fine particulate matter from the regulatory frameworks is rectified.

5.5 Recommendations

Direct access to the primary treatment area should be prohibited due to the risk of physical injuries from rocks and high levels of particulate matter emissions in the area. Regular risk assessments should be carried out to quantify the amount of dust emission in order to inform hazard control mechanisms around the quarry area.

Restrict access to only control rooms and make sure only vehicles with enclosures are allowed around the plant to prevent exposure to dust emissions. People must never be allowed to walk freely outside their vehicles.

The admin block/building complex should be regarded as a high dust exposure area and necessary dust abatement measures should be in pace. When it is very windy and highly dusty the use of additional PPE may be justified.

Occupational hygiene surveys performed around the plant must include measurement of submicron particles to quantify the number of emissions and possible exposure to UFP's and occupational exposure.

Medical surveillance programs must be designed to address potential exposure to UFP and FPM. Controls that are in place must also be adapted to also cater for exposure to small particles, and policies must be amended to feature occupational exposure to fine particulate matter.

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APPENDIX 1 – PLAGIARISM DECLARATION

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF HEALTH SCIENCES

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

I DANKISO DAVID MKWANAZI (Student number: 1091664) am a student registered for the degree of M. Sc. Med. Exposure Science in the academic year _______.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature: __________ Date: 2023-01-23

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APPENDIX 2 – TURNITIN REPORT

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by Dankiso Mkwanazi

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Dr Masilu Masekameni

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APPENDIX 3 – ETHICS CLEARANCE

Ethics clearance was not required since the study did not involve any humans or animals. Only ambient air sampling was performed and no human or animal samples were collected.