Assessment and Control of Respirable Crystalline Silica in Quarries and Dimension Stone Mines

By

Kevin John George Hedges

BSc, DipEd, M.App.Sc.,

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School of Science and Health
Western Sydney University

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CERTIFICATE OF ORIGINALITY

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

Kevin John George Hedges

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I dedicate this thesis to my late father, John George Thomas Hedges, whose perseverance and strength of character still resonates with me many years after his death. I will always be grateful to my dad, a family man and hard worker, who for many years worked two jobs to give his family a better life.
He cared for his community as a fire fighter and first aider.

Based in Maralinga in Australia for the British nuclear testing, working with Bristol Fire Brigade in England, and then in later in life, working in underground Australian coal mines, for about twenty years, which included roof bolting saw him exposed to a cocktail of health hazards. His life was cut short at 57 from lung cancer. His passion for life still lives in me.

This thesis is not only for my dad, but for all of the other hard workers who unknowingly, breathe in hazardous dust that will not only rob them of enjoying their family into old age, but also impact those who love them.
I am eternally grateful to Stacy (my wife), and Cohen my 5 year old boy, for their sacrifices with my absence to complete this research and for their love and support through this period of transition.

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Hopefully this work will live on!

ABSTRACT

The health risk of breathing very fine particles of respirable crystalline silica (RCS) dust, resulting in poor lung health is not well defined in Australia, even though many hundreds of thousands of workers are exposed to uncontrolled dusty activities daily.

It is now clear from international studies that lung health of workers continues to be affected at relatively low exposures to RCS, even at occupational exposure limits (OEL) including the current Safe Work Australia Exposure Standard (SWA-ES). This has prompted the United States to reduce their permissible exposure limit (PEL) to one half of the Australian SWA-ES, to 0.05 mg/m^3, and challenges the adequacy of the current Australian SWA-ES, which is 0.1 mg/m^3. In terms of numbers of workers affected, the mining industry employs approximately 267,000 workers, which is 2.3 percent of the total workforce, and accounts for about 10.2 % of Australia's Gross Domestic Product (GDP).

Approximately 55,000 workers are employed in Queensland mining, many of whom work in quarries and dimension stone mines where exposure to RCS is known to be elevated. A recent assessment estimated that about 440,000 deaths from cancer attributable to RCS exposure will occur throughout Europe from 2010 to 2069. Unless exposure to RCS is well controlled, many hundreds of thousands of lives will also be cut short from silicosis and chronic obstructive pulmonary disease (COPD). As the weight of evidence grows in Australia, the disease risks attributable to RCS will increasingly become more obvious.

This study evaluated the health risk from exposure to RCS for 47 quarry and dimension stone mine workers throughout Queensland, Australia. Personal exposures to RCS were measured across a range of exposures, and lung function testing was carried out in parallel. Findings revealed that about one in four workers were exposed to RCS above the SWA-ES, and more than one in ten were being exposed at a concentration of more than twice this limit. A major

finding for those workers exposed to RCS at the SWA-ES was loss of lung function greater than 20%. The increased loss of lung function was positively correlated with jobs associated with increased RCS exposure. When similar exposure groups were combined into three RCS exposure ranges categorised as high (≥ 0.09 - ≤ 0.20 mg/m^3), medium (≥ 0.04 - ≤ 0.08 mg/m^3) and low (< 0.04 mg/m^3), analysis of variance (ANOVA) confirmed that the loss of lung function below the lower limit of normal (LLN) at the current SWA-ES, is significant ($p < 0.05$). Abnormal lung function patterns were also more pronounced for smokers who were exposed to RCS ≥ 0.04 mg/m^3 and not as obvious for smokers exposed to RCS < 0.04 mg/m^3. This demonstrated that both smoking and RCS had a combined impact resulting in poor lung health.

In this study, vehicles fitted with standard heating, ventilation and air-conditioning systems (HVAC) were tested for ingress of respirable dust into the operator's cabin, and compared with more recent technology. Evaluation of the effectiveness of newer technology, a RESPA® pre-cleaner, filter and pressurization (PFP) unit, demonstrated up to a four-fold reduction in RCS entering the cabin, when compared with standard air-conditioning systems.

Electron microscopy (EM) was used to describe the physical characteristics of respirable silica and dust particles collected on respirable sample filters previously analysed for silica by infrared spectroscopy. Data revealed that silica particles were generally less than 5 μm in physical diameter and many particles were elongated. These smaller particles are known to be most hazardous to lung health. Findings also demonstrated that larger length elongated particles were collected by the cyclone sampler, which influenced the particle size distribution curve. There was a good fit between the physical cumulative silica particle size distribution, representing particle counts for selected workplace samples, when plotted against the theoretical AS2985-2009 (density dependent) Equivalent Aerodynamic Diameter (EAD) sampling efficiency curve. This means that density is not the only factor for particle capture in the cyclone sampler. These silica particles do not behave as perfect spheres, which is the

premise underpinning the International Organization for Standardization (ISO) 7708-1995, sampling efficiency curve and AS2985-2009, adopted by the Australian Standard for sampling respirable dust. The science for these standards is based on information that is at least twenty years old, and results from the current study confirmed that particle shape must be considered in the sampling efficiency curve and lung health risk assessment.

An unexpected finding from analysis of RCS dust by EM was the identification of fibrous mineral particles in several samples, with both morphology and elemental composition similar to erionite. Erionite is known to cause mesothelioma, which is typically associated with asbestos when inhaled at high enough concentrations. Further investigation and characterization of respirable dusts at mining sites where erionite is a potential contaminant is recommended. Confirmation of the presence and extent of erionite, and further characterization of exposure will assist in determining the extent of health risk to quarry and dimension stone mine workers in Queensland and elsewhere.

Overall, the findings from this study challenge the adequacy of RCS health risk assessment standards in Australia. In addition, typical operator cabin air-conditioning technology will not reduce exposure to RCS where silica is present in dusty workplaces.

The study also demonstrates the importance of health surveillance, to identify gaps, raise awareness about primary prevention, and drive timely intervention.

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GLOSSARY

Term	Definition
Average	Arithmetic mean
Air Conditioning	The process whereby air is treated to meet the temperature, humidity, cleanliness and distribution requirements of a space
Chronic Obstructive Pulmonary Disease	Chronic obstructive pulmonary disease (COPD) is a lung ailment that is characterized by a persistent blockage of airflow from the lungs. It is an under-diagnosed, life-threatening lung disease that interferes with normal breathing and is not fully reversible. The more familiar terms of chronic bronchitis and emphysema are no longer used; they are now included within the COPD diagnosis (World Health Organization 2015).
Coarse Particulate Matter	Particulate matter measuring 2.5 to 10 µm in diameter (Environmental Protection Agency 2013)
Confidence limits	The upper and lower boundaries of a confidence interval. Upper confidence limit is abbreviated UCL; lower confidence limit is abbreviated LCL.
Fine Particulate Matter	Particulate matter measuring < 2.5 µm in diameter (Environmental Protection Agency 2013)
High Risk Respirable Fraction	Respirable fraction often referred to as respirable in environmental of public health publications and is defined as the particle size which is hazardous to respiratory health. Also more hazardous to at risk populations such as the elderly is the median diameter of 2.5µm ($PM_{2.5}$) (ISO 1995).
Lower Limit of Normal	The lower limit of normal (LLN) is equal to the 5^{th} percentile of a healthy population (Culver 2012).
Minimum Variance Unbiased Estimate	Best estimate of the average for a log-normally distributed data set.
Personal monitoring	Personal sampling of air within the breathing zone which is within 30cm of the nostrils (Standards Australia 2009).
$PM_{1.0}$	Particulate matter less than 1 µm in diameter (Rundell et al. 2007)
$PM_{2.5}$	Particulate matter with a median (50%) aerodynamic diameter of 2.5 µm in diameter (International Organization for Standardization 1995).

PM_{10}	Particulate matter < 10 µm in diameter (Environmental Protection Agency 2014)
Real Time Monitoring	The use of instruments that can provide instantaneous results on aerosol, gas or vapour concentrations
Respirable dust	The fraction of inhaled particles that penetrate to the alveolar region of the lung, with 50% penetration at 4.25 µm AS2985-2009 (ISO 1995; Standards Australia 2009).
Respirable crystalline silica	In order for the crystalline dust particles to reach the extremities of the lung where they have the potential to do damage, they must be particularly small (less than 10µm in diameter), and this size is defined as "respirable". Therefore we call the toxic form of this dust "respirable crystalline silica" or RCS. RCS is sampled using AS2985-2009 (Standards Australia 2009).
Safe Work Australia – Exposure Standard	Workplace exposure standards are airborne concentrations of a particular chemical or substance in the workers' breathing zone that should not cause adverse health effects or cause undue discomfort to nearly all workers. Exposure standards are legal concentration limits that must be adhered to. An eight-hour time-weighted average exposure standard is the average airborne concentration of a particular substance permitted over an eight-hour working day and a 5-day working week. These are the most common types of exposure standards. *Note: 8-Hour TWA exposure standards may require adjustment where work shifts exceed 8 hours or for greater than a 5-day working week.* (Safe Work Australia 2013b)
Safe Work Australia	Safe Work Australia is a tripartite body. Safe Work Australia is responsible for coordinating and developing national policy and strategies, developing model work health and safety (WHS) laws, undertaking research and collecting, analysing and reporting data. Safe Work Australia works collaboratively with work health and safety regulators, industry groups and unions to achieve the national vision of *healthy, safe and productive working lives*.
Site Senior Executive	Site Senior Executive (SSE) is the most senior person on site who is responsible for the operation under the Queensland Mining & Quarrying, Act & Regulation.

Similar Exposure Group	A Similar Exposure Group (SEG) is defined as "A group of workers having the same general exposure profile for an agent because of the similarity and frequency of the task (s) they perform, the similarity of materials and processes with which they work, and the similarity of the way they perform the tasks (Mulhausen 2006).
Ultrafine particulate matter	Particulate matter measuring < 100 nm in diameter (Environmental Protection Agency 2015)

ACRONYMS

Acronym	Meaning
ACGIH	American Conference of Governmental Industrial Hygienists
ACOEM	American College of Occupational and Environmental Medicine
AE	Long term estimated average exposure
AIOH	Australian Institute of Occupational Hygienists
ANOVA	Analysis of Variance
AS	Australian Standard
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BPTS	Body temperature and pressure saturated
BOHRF	British Occupational Health Research Foundation
BMRC	British Medical Research Council
BOHS	British Occupational Hygiene Society
CEN	European Committee for Standardisation
CAL	Chronic airway limitation
CAO	Chronic airflow obstruction
CC16	Clara cell protein
CI	Confidence interval
COAD	Chronic obstructive airway disease
COPD	Chronic Obstructive Pulmonary Disease
CWHSP	US Coal Workers Health Surveillance Programme
CWP	Coal Workers Pneumoconiosis
df	Degrees of freedom
DNA	Deoxyribonucleic acid
DME	Queensland Department of Mines and Energy
EAD	Equivalent Aerodynamic Diameter (also referred to as *dpa*)
EDS	Energy dispersive spectroscopy
FEV_1	Forced Expired Volume in 1 Second
FTIR	Fourier Transform Infrared Spectroscopy
FVC	Forced Vital Capacity
GOLD	Global Initiative for Chronic Obstructive Lung Disease Inc.

GSd.	Geometric standard deviation
HRQL	Health-related quality of life
HE	Highest annual estimated average exposure
HRCT	High-resolution computed tomography
HREC	Human Research Ethics Committee
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
HVAC	Heating, ventilation and air-conditioning
IARC	International Agency for Research on Cancer
ICRP	International Commission for Radiological Protection
IRAS	Institute for Risk Assessment Sciences
IOM	Institute of Occupational Medicine
ISO	International Organisation for Standardisation
KIM-1	Kidney injury molecule-1
LCL	Lower confidence limit
LLN	Lower Limit of Normal
LN	Log-normal
LOD	Limit of detection
LoQ	Limit of quantitation
MRE	Mine Record Entry
MD	Medical Doctor
MMAD	Mass Median Aerodynamic Diameter
mppcf	Millions of particles per cubic feet
MRC	Medical Research Council
MRCQ	Medical Research Council Questionnaire
MRE	Mine Record Entry
MVUE	Minimum variance unbiased estimate
NGAL	Neutrophil gelatinase -associated lipocalin
NHANES	National Health and Nutrition Examination Survey
NHMRC	National Health and Medical Research Council
NIOSH	National Institute for Occupational Health and Safety
NOAEL	No Observable Adverse Effects Level

NTP	National Toxicology Program
NVva	Dutch Occupational Hygiene Society
OEL	Generic term for Occupational Exposure Limit
OEHHA	Office of the Environmental Health Hazard Assessment
OR	Odds Ratio
OSHA	Occupational Safety and Health Administration
PAT	Proficiency Analytical Testing
PEMs	Personal exposure monitors
PFP	Pre-cleaner, filter, pressurization
PM	Particulate matter
PMF	Progressive Massive Fibrosis
ppcc	Particles per cubic centimetre
PPD	Purified protein derivative
PVC	Polyvinyl chloride
RCS	Respirable crystalline silica
RNS	Reactive nitrogen species
ROS	Reactive oxidative species
RPE	Respiratory protective equipment
SEG	Similar Exposure Group
SEM	Scanning Electron Microscopy
SGRQ	St George's Respiratory Questionnaire
SQRT	Square Root
SPIROLA®	Spirometry Longitudinal Data Analysis
SSE	Site Senior Executive
SWA	Safe Work Australia
SWA - ES	Safe Work Australia Exposure Standard
TLV	Threshold Limit Value
TSP	Total suspended particulate matter
TWA	Time Weighted Average
WHO	World Health Organisation
UCL	Upper confidence limit
UTL	Upper tolerance limit

UK	United Kingdom
USA	United States of America
UWS	University of Western Sydney
WA	Western Australia
WEL	Workplace Exposure Limit
XRD	X-ray diffraction (XRD)

Journal papers, conference papers, presentations and abstracts arising from this study:

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2. Hedges, K 2014, Assessment and control of respirable crystalline silica (RCS) in quarries in Queensland Australia, *Proceedings of the 7th International Symposium: Safety and Health in Agriculture and Rural Populations: Global Perspectives.* 7th International Symposium, Saskatoon, SK, Canada October 19 – 22, 2014.

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1. Department of Natural Resources and Mines (DNRM) 2010, Management of dust containing crystalline silica (quartz). Safety Bulletin 88. Queensland Government, Mines Inspectorate. Published 23 February 2010.

2. Department of Natural Resources and Mines (DNRM) 2009, RESPA™ Trial 2009 Occupational Hygiene Monitoring for airborne particulate matter and respirable crystalline silica inside of an excavator cabin – before and after fitting a pre-cleaner filter and pressurisation unit. File 042066. Queensland Mines Inspectorate. The report has also been provided via Sy-Klone International

3. Department of Natural Resources and Mined (DNRM) 2008, Questionnaire feedback – respirable crystalline silica File 040861. Report provided back to the metal mining and quarrying industry in response to a questionnaire sent in March 2008. Final report prepared 1 July 2009.

CHAPTER 1 Introduction

The health impact of exposure to silica dust has been known since the start of the industrial revolution. Exposure to respirable crystalline silica (RCS), a common mineral in mining and quarrying operations, results in the lung damaging diseases known as silicosis and chronic obstructive pulmonary disease (COPD) (National Institute of Occupational Safety and Health (NIOSH) 2002). The societal legacy of lung disease from silica dust exposure is acknowledged from the following lyrics by James Gordon from his song 'Mining for Gold' (2002):

> Can't you feel the rock dust in your lungs?
> It'll cut down a miner when he is still young
> Two years and the silicosis takes hold
> and I feel like I'm dying from mining for gold

The current international impact is reported by the media. For example,

Smith (2012) reported:

> South African gold miners file lawsuit against industry giants for negligence. Lawyer representing gold miners with lung disease says case could become largest damages suit in South African history. Lawyers say AngloGold, Ashanti, Gold Fields and Harmony could face record damages if the court recognises their case as a class action.
>
> 'In July 2014, 15,000 former miners suffering from lung disease joined South Africa's biggest ever class action lawsuit against some of the world's leading gold producers' (Jamasmie 2014).

Acute silicosis which can be caused by sand blasting appears to be uncommon in Australia. However, the magnitude of health impacts, including chronic silicosis, resulting from longer term exposures around the Safe Work Australian Exposure Standard (SWA-ES) of 0.1 mg/m^3 crystalline silica dust is not well understood.

Other illnesses attributable to silica, known to pose a global legacy, include COPD (Driscoll et al. 2005) and cancer (Castranova & Vallyathan 2000; NIOSH 2002; Driscoll et al. 2005; International Agency for Research on Cancer (IARC) 2012; Liu et al. 2013; Steenland & Ward 2014). Internationally, there is compelling evidence to show that the burden from long term exposure to airborne levels of RCS typically generated from industrial activities is significant. A recent assessment by Cherrie (2012) estimated that 440,000 deaths from cancer attributable to RCS exposure will occur throughout Europe from 2010 to 2069. There has been considerable debate in Australia about what is considered a suitable SWA-ES. Some dose response studies (Health and Safety Executive (HSE) 2002) have shown that silicosis normally occurs in workers many years after exposure has ceased, and who were exposed to RCS levels previously accepted as low risk. Quarries, mines and exploration sites undertake many dust generating activities that expose workers to dust inhalation. The potential for lung disease increases as exposures increase and this has been shown over a range from 0.02 mg/m^3 to 0.3 mg/m^3 (HSE 2002). Health effects from exposure to silica have been reported extensively in the literature but research showing dose response relationships, including workplace measurements around 0.1 mg/m^3, the SWA-ES, and health effect outcomes are lacking.

A complicating factor is diagnosis. De-Klerk et al. (2002, p. 688) noted that:

> 'simple silicosis can be asymptomatic and have no significant effect on lung function'.

Analysis of historical exposure monitoring records has been hampered by changes to measurement techniques over time. Sampling methods have evolved to better replicate the human breathing system and match how dust enters the lung (International Organization for Standardization (ISO) 1995; ISO 2012). The trade-off is that conversion factors have been estimated to allow comparison of

old measurements with more recent measurements. This adds another level of uncertainty and complexity to the overall characterisation of exposure.

Monitoring the health of workers to assess disease progression involves a number of complimentary tests such as full chest x-rays, spirometry and respiratory questionnaires. All tests are important and when combined they provide a comprehensive assessment and early diagnosis for occupational disease.

The Standards Australia (SA) method for measuring exposure to respirable dust AS2985-2009 (SA 2009) and RCS uses a personal monitoring technique in accordance with the internationally accepted particle size-selective sampling criteria of the respirable fraction for airborne particulate matter (ISO 1995). Measuring RCS at low enough concentrations is limited by instrument and analytical sensitivity and interferences from other contaminants in workplace air (Stacey 2007). In a number of situations the concentration of RCS that can reliably be measured is limited to exposures ≥ 0.02 mg/m^3 making it difficult when assessing exposures against the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value of 0.025 mg/m^3 (ACGIH 2013).

Mine and quarry workers breathe in dust containing RCS due to the nature and dustiness of the activities such as crushing and screening. Predicting the health potential risk of low level exposure to respirable crystalline silica is not possible in Australia due to lack of available exposure data coupled with results from health surveillance. Silicosis is considered to be a slowly developing and progressive disease, not always diagnosed during a working life. Personal exposure monitoring and evaluating the efficacy of controls will provide a better estimate of the extent of exposure during working life and will guide development of standards to assist with assessment of the risk for developing silicosis. There are a number of studies that reported the relationship between loss of lung function and cumulative exposure to respirable dust and RCS (Meijer et al. 2001; Ulvestad et al. 2001). In some of these studies exposure to

RCS below the Safe Work Australia (SWA) (2012a) exposure standard (ES) – time weighted average (TWA) for an 8 hour work period, of 0.1 mg/m^3 was associated with loss of lung function.

Since 1997, the International Agency for Research on Cancer (IARC) has documented RCS as a Group 1 carcinogen in humans ((IARC 1997).

According to SWA, (2013b, p.5):
Exposure standards do not identify a dividing line between a healthy or unhealthy working environment. Natural biological variation and the range of individual susceptibilities mean some people might experience adverse health effects below the exposure standard. Therefore, exposure standards should not be considered as representing an acceptable level of exposure to workers. They establish a statutory maximum upper limit.

The current SWA-ES for the most common form of RCS, respirable quartz, is 0.1 mg/m^3 (SWA 2013a). In a review of causes of silicosis (HSE 2002) it was acknowledged that exposure to crystalline silica at concentrations below 0.1 mg m^3 over a long period could lead to silicosis.

This quantitative risk estimate for silicosis was based on a study of hundreds of workers from a Scottish coalmine where major seams of sandstone were encountered in one part of the mine (HSE 2002). Of particular significance in that study was that workmen were monitored for an exposure period of about 10 years while they mined through sandstone to extract coal. A group of workers with measured exposures to RCS at concentrations down to 0.1 mg/m^3 would therefore provide a dose response curve at relatively lower concentrations using actual data (HSE 2002). Risk estimates from that study can be seen in Table 1.1.

Table 1.1: Estimated quantitative risks of developing silicosis (2/1+)
(Source: HSE 2002, p73)

15 years daily exposure to respirable crystalline silica dust at average airborne concentrations for an 8-hour shift in mg/m^3	Risk of developing silicosis within 15 years following cessation of exposure
0.02	0.25 %
0.04	0.5 %
0.1	2.5 %
0.3	20 %

In the review of Scottish miners (HSE 2002), only workers exposed to freshly cut surfaces of RCS generated by mechanical cutting into sandstone were included. The HSE considered that the risk estimates presented in Table 1.1 are likely to have widespread relevance and applicability.

NIOSH have also estimated the prevalence of silicosis in the United States of America (NIOSH 2002). NIOSH provided a number of studies that predicted the incidence of silicosis to be approximately 1 to 7 silicosis cases per 100 workers at respirable quartz concentrations of 0.025 mg/m^3. Cumulative exposure, not average exposure, has also been noted as the best predictor for disease (Steenland et al. 1995). To prevent the progression of adverse health ongoing health surveillance including a lung function test (spirometry) is an important predictor of lung disease although spirometry alone cannot be used to diagnose any particular disease. NIOSH suggested that although lung function tests can measure impairment, the test is not a diagnostic tool for silicosis alone, nor a measure of silica exposure, because no single pattern of abnormality exists (NIOSH 2002). NIOSH also refers to studies where cumulative exposure to respirable dust containing silica is strongly correlated with loss of lung function and adverse health effects (NIOSH 2002). Ongoing

research is needed to determine the relationship between occupational exposure to silica dust and clinically significant changes in lung function.

Ghotkar et al. (1995) noted that when stone quarry workers are exposed to silica dust at concentrations within the permissible range, and measured as cumulative dust exposure, there is a risk of impaired lung function. There are studies (Ulvestad et al. 2001; Glass et al. 2003) that have quantified the annual loss of lung function in mL per year. The data values from these studies are inconsistent and it is not obvious, from the literature, whether the dose response curves are based on exposure estimates made from statistically valid occupational hygiene monitoring data. NIOSH (2002) and the American College of Occupational and Environmental Medicine (ACOEM) (2006) noted that significant decrements in lung function, and respiratory symptoms are unlikely in the early stages of silicosis. ACOEM (2006) also recommended that both cross sectional and longitudinal spirometry needs to be carried out to provide better estimates of risk. Longitudinal spirometry monitors the health of a worker over time, which means that their lung function tests can be compared with their baseline test, whereas cross sectional testing is carried out to assess lung function against predicted values. Where spirometry is undertaken in conjunction with an exposure study, a cross sectional dose response curve can be used as a way to quantitatively estimate the risk. In cases where occupational exposures to RCS have been estimated, no statistically valid exposure monitoring data were found nor was any comparison undertaken with loss of lung function.

Buchanan, Millar & Soutar (2003, p.159) noted that:

> Quantification of the risks of silicosis should take into account variations in quartz exposure intensity, particularly for exposure to concentrations of greater than 1 or 2 mg/m^3, even if exposure is for relatively short periods.

Real time monitoring can be used to identify events and potential duration of high exposure. Evaluation of sampling methods to understand particle size

distribution and the relationship of crystalline silica in the host rock and RCS is also important. Real time analysis of different sizes of dust particles will identify processes and activities that produce airborne dust within size fractions.

Gupta et al. (2005) noted that crystalline silica particles less than 1 μm are believed to be most pathogenic. Characterisation of particle size distribution at work sites will assist in providing control technology designed specifically to wet and suppress respirable dust, such as air filtration and conditioning systems.

An Australian senate inquire on workplace exposure to toxic dusts in 2006 noted that potential adverse health outcomes from RCS exposure should have a high research priority (Faunce et al. 2006).

1.1 Background

Responses to questionnaires sent out from the Queensland Department of Mines and Energy (DME) to Site Senior Executives (SSE) at 420 mines, quarries and exploration sites throughout Queensland, Australia in 2008, revealed that there was a low level of awareness about the health effects of RCS (DME 2009a). Of the 420 questionnaires, replies were received from 131 sites which equates to 31% of respondents. Analysis of these data showed that risk management controls, including awareness training, respiratory protective equipment and engineering controls were sub-optimal. It was also evident in that study, that many sites do not conduct personal monitoring, and only about 50% of sites surveyed conducted health surveillance (DME 2009a). In February 2010, a safety bulletin was released as a follow-up to the DME (2009a) survey on the Queensland Government web-site (DME 2010). The safety bulletin noted that many mining and quarrying sites may not be adequately addressing the risk of RCS exposure, resulting in the potential for adverse health effects from RCS. Communication was provided through this bulletin that chronic exposure to RCS, even at relatively low levels, may lead to chronic silicosis many years after a worker has retired (DME 2009a).

A recent publication produced in 2010 by the United Kingdom Health and Safety Laboratory (HSL), RR827: Health surveillance in silica exposed workers, HSL, (2010, p.6) noted:

> In parallel to the development of a standardised approach, further GB-based work with workers and employers should be carried out to gain, from a retrospective assessment of health surveillance data, a better understanding of the local context. Specifically, a better understanding could be developed of the ideal periodicity of the various components of health surveillance and of predictive factors that are associated with the development of silicosis, accelerated lung function decline and COPD.

Based on the findings from the DME (2009a) survey it was concluded that workers in mining throughout Queensland may be at risk from exposure to RCS and associated adverse health effects. Subsequent exposure assessment and lung function testing, for a selection of workers in quarries and small mines across Queensland may in fact be used to predict adverse irreversible health outcomes.

1.2 Aim and objectives

The aim of this project was to determine the potential impact to respiratory health from exposure to airborne crystalline silica, in Queensland quarries and dimension stone mines.

The objectives of the study were to:

- Measure personal exposure for a cross section of quarry and dimension stone workers.
- Evaluate the effectiveness of cabin air-filtration RESPA® technology in reducing operator exposure to RCS compared with conventional cabin heating, ventilation and air conditioning (HVAC) systems.
- Analyse the relationship between spirometry, respiratory symptoms and exposure assessment

- Use electron microscopy to evaluate particle size distribution, and shape, to identify physical characteristics responsible for these particles being entrained in breathing air, and reaching the lung resulting in adverse lung health.

This research project was carried out with the approval of the UWS human research ethics (HREC approval H6548). Copy attached in Appendix A.

CHAPTER 2 Literature Review

Searches were carried out through the Western Sydney University Library e-resources section via Ovid. Medical journals such as The Lancet, were researched for historical articles. Select occupational hygiene journals, such as the Annals of Occupational Hygiene, and Journal of Occupational Hygiene and Environmental Hygiene, were reviewed in addition to using snowball methodology to source secondary citations. The grey literature was also searched using both google and google scholar and government references were obtained through the UK HSE, SWA, NIOSH and Occupational Health and Safety Administration (OSHA) internet sites. Australian and international standards were sourced through the Standards Australia internet site.

Searches were carried out using a combination of keywords including: silica, silicosis, `respirable crystalline silica`, quartz, erionite lung function, spirometry, `health surveillance`.

2.1 History

A stone-mason, aged 37, was admitted into the Manchester Infirmary on Feb. 4, 1880, and died a week after admission from excessive breathing difficulty. The symptoms observed during life were mainly those of bronchitis. Lungs from other patients showed an increased quantity of silica. It was revealed that the disease was not only caused from tuberculosis, as previously thought.

The term pneumo-koniosis was a generic term first described by Zenker (cited in Harris 1881). Silicosis pulmonum was chemically characterised by the presence of large amounts of silica in the lung and by the presence of numerous hard nodules.

The three stages of progression were noted to be:

1) cough, with sputum containing silica;
2) physical signs of patches of pneumonia; and
3) night sweats and the physical signs of lung cavities (Harris 1881).

The history suggests that when silicosis was first described and attempts were first made to classify the disease, it is likely that misdiagnosis was common.

Harris (1881, p.398) noted that:

> In one of the cases of a mill-stone maker, tubercles are described as existing in the lungs in masses, with the interposed pulmonary tissue comparatively sound; yet in the record of the microscopical examination of the diseased portions, nothing is said about tubercles. It being stated that the diseased masses appear to be made up of dense closely arranged fibroid tissue, studded here and there with numerous irregular groups of black pigment, and generally with an abundance of granules and globules of various sizes. Whether these cases belong to the class, or were really tuberculous, does not seem quite clear.

There was confusion at the time and The Lancet (1885) questions why symptoms were dropped, which had been previously used to classify disease in favour of what caused the disease, or 'morbid states underlying them' (The Lancet, 1885, p.854).

The Lancet (1885, p.854) asks the questions:

> Why are the terms acute pneumonic and chronic pneumonic prefixed to phthisis? For what reason is it preferred to use the phrase black induration rather than iron-grey induration of the lung? or, to retain millstone-maker's phthisis, grinder's asthma and miner's asthma, instead of recognising the existence of a group of diseases due to inhalation of dust, and classing silicosis, anthracosis, as their varieties? There is altogether a lack of grasp in this section, or at any rate a want of appreciation of the distinctions created by modern pathological inquiry.
>
> An early attempt to classify lung conditions is summarised in Table 2.1.

Table 2.1 - An early attempt to classify different lung diseases.
(Source: Harris 1889, p.992)

<table>
<tr><th colspan="2">Tubercular phthisis</th><th colspan="5">Non-Tubercular phthisis</th></tr>
<tr><td>Caseous pneumonia.</td><td>Tubercular peribronchitis</td><td colspan="4">Fibroid phthisis</td><td>Non bacillary phthisis of diabetics</td></tr>
<tr><td colspan="2"></td><td>Chronic croupous pneumonia</td><td>Chronic cattarhal pneumonia</td><td colspan="2">Chronic interstitial pneumonia</td><td></td></tr>
<tr><td colspan="4"></td><td>Primary corrigans cirrhosis</td><td>Secondary pneumo-koniosis</td><td></td></tr>
<tr><td colspan="5"></td><td>Anthrasosis</td><td></td></tr>
<tr><td colspan="5"></td><td>Silicosis and chalicosis</td><td></td></tr>
</table>

A clinical lecture delivered by Harris (1889) to students of the Manchester Royal Infirmary was published in the Lancet, titled "The varieties of pulmonary phthisis". Phthisis means a disease causing wasting away of part, or all of the body, such as tuberculosis. The lecture raised concern about differences in classification made between the Physician and Pathologist. It was noted that the Physician used terms to identify phthisis from bedside symptoms but these terms were not used by the pathologist.

The lecture as noted by Harris (1889, p.989) stated that:

> 'The difference in terms is indeed a very unfortunate one'.

It was not until the clinical experience was paired with observation by post-mortem that a clearer understanding about the cases and possible causes of phthisis was obtained (Harris 1889).

At that time pathologists recognized two cases of phthisis:

One group of cases was caused by tubercle, usually mycobacterium tuberculosis. Harris (1889), referred to the other group as non-tubercle phthisis being rare.

Different forms of the non-tubercle group included Corrigan's cirrhosis and pneumo-koniosis, which occur as a result of inhaled dust from work performed, such as stonemasons inhaling silica. Corrigan's cirrhosis was the term used for acute diffuse interstitial pulmonary fibrosis from an unknown cause (Harris 1889).

The term Pneumoconiosis is now used to describe a group of lung diseases caused by inhaled dust particles. Pneumoconiosis can lead to lung impairment, disability, and premature death (NIOSH 2012a). It is also now known that there is an interaction between silicosis and tuberculosis which causes a condition known as silico-tuberculosis.

An investigation of Cornish miners in 1902, cited in Brink et al. (1960 p.959), reported that:

> 'Stone dust pre-disposes enormously, to tuberculosis in the lung'.

In Australia by 1910, death from miners' phthisis, including tuberculosis (silico-tuberculosis) or silicosis was widespread Bowden & Penrose (2006) as seen in Table 2.2.

Table 2.2 Statistics showing the number and % of miners that died as a result of pneumoconiosis. The Royal Commission, into Miners' Phthisis, 1911 (cited by Bowden & Penrose 2006).

Location	Period	Deaths rate per 10,000 living workers	%
Queensland, Australia	1906 to 1910	42.2	0.4
Western Australia	1900 to 1906	53.9	0.5
Bendigo, Victoria, Australia	1900 to 1906	191.6	1.9

While acknowledging that their data was limited, the Commissioners nevertheless concluded, as stated by Bowden & Penrose (2006, p.19), that:

'Queensland miners had a relatively low death rate from lung diseases'.

In the United States, construction of the Hawks Nest Tunnel, which started in 1930 and took 18 months to complete, employed about 5000 workers. The tunnel drilled through rock with a high percentage of silica. According to McCulloch & Tweedle (2013), the drills were run dry without water suppression, the ventilation was minimal, and there were no basic hygiene facilities such as respirators, overalls or washing facilities. Although the number of fatalities are estimated to have exceeded 750 with another 1,500 workers with respiratory disease, there were conflicting reports about whether the disease responsible for the primary health effect was in fact silicosis. Nevertheless follow up studies demonstrated that the occupational disease was predominantly acute silicosis, and in many instances, workers contracted this disease within a year of commencing employment (McCulloch & Tweedle 2013).

2.1.1 Historical exposures to dust containing silica

To understand historical exposures to dust, it is necessary for this to be discussed along with changes in methods of monitoring dust inhalation.

A number of researchers Hewson et al. (1996); Verma et al. (2010); Sun et al. (2011), have attempted to estimate historical exposure measurements to dust inhalation in some workplaces and compare these estimates with current standard methods. Prior to the current gravimetric sampling method, different sampling methods were used to estimate levels of airborne dust. The impinger, konimeter and thermal precipitator particle count tests were the common methods used at the time as shown in Table 2.3.

Table 2.3: Summary of methods for assessing exposure to airborne silica between 1916 and 2009

Years	Device	Description	Measure	Reference
1916	Konimeter	Deposition by impaction onto greased glass plates, counting of particles (light microscope)	Particle count. Particles per mL and related units. Grab sampling.	Harper, 2006
1925 - 1977	Konimeter	Used to measure Western Australian miners exposure to airborne dust	Particles per cubic centimetre. Grab sampling.	Hewson, 1996
1922	Impinger	Sampling into a liquid, counting of particles (light microscope).	Millions of particles per cubic feet (mppcf) and related units. Grab sampling.	Harper, 2006
1935	Thermal precipitator	Deposition by thermal movement onto plates counting of particles (light microscope).	Particle count. Grab sampling.	Harper, 2006
1950	Konimeter	Kotze konimeter was replaced by a Watson Victor circular konimeter	Particles per cubic centimetre. Grab sampling.	Hewson, 1996
1954	Thermal precipitator and horizontal elutriator	The horizontal elutriator was added to the thermal precipitator in 1954 in the UK in order to separate the numbers of fine particles from course.	Particle count. Grab sampling.	Harper, 2006
1961	Konimeter	In 1961, a different type of illuminator was used with the konimeter, which revealed that there were differences in the particle size collected by each of these konimeters	Particles per cubic centimetre. Grab sampling.	Hewson, 1996
Late 1960 to1970s (USA and Australia)	Cyclone	Standards changed from particle count to mass.	Gravimetric method. BMRC/ Johannesburg convention. Longer term sampling representative of exposure over a shift.	Harper, 2006
1987	Cyclone	AS 2985 -1987	BMRC (British Medical Research Council) sampling curve with a 50% cut in the efficiency collection of 5.0 µm at a flow rate of 1.9 L/min.	Standards Sustralia 1987, AS2985 - 1987
2004	Cyclone	AS 2985 -2004	Adopted the ISO/Soderholm sampling curve with a 50% cut in the efficiency collection of 4.25 micrometers. Flow rate changed to 2.2 L/min to match curve.	Standards Australia 2004, AS2985 - 2004
2009	Cyclone	AS 2985 -2009		Standards Australia 2009, AS2985 - 2009

2.1.1.1 Western Australian (WA) Miners.

A study of Western Australian miners by Hewson (1996), estimating exposures between 1925 and 1993 demonstrated reduced exposure to respirable dust (Figure 2.1). These estimates were modelled from a measurement method that used different types of konimeter (refer to Table 2.3) to monitor short-term exposures between 1925 and 1977.

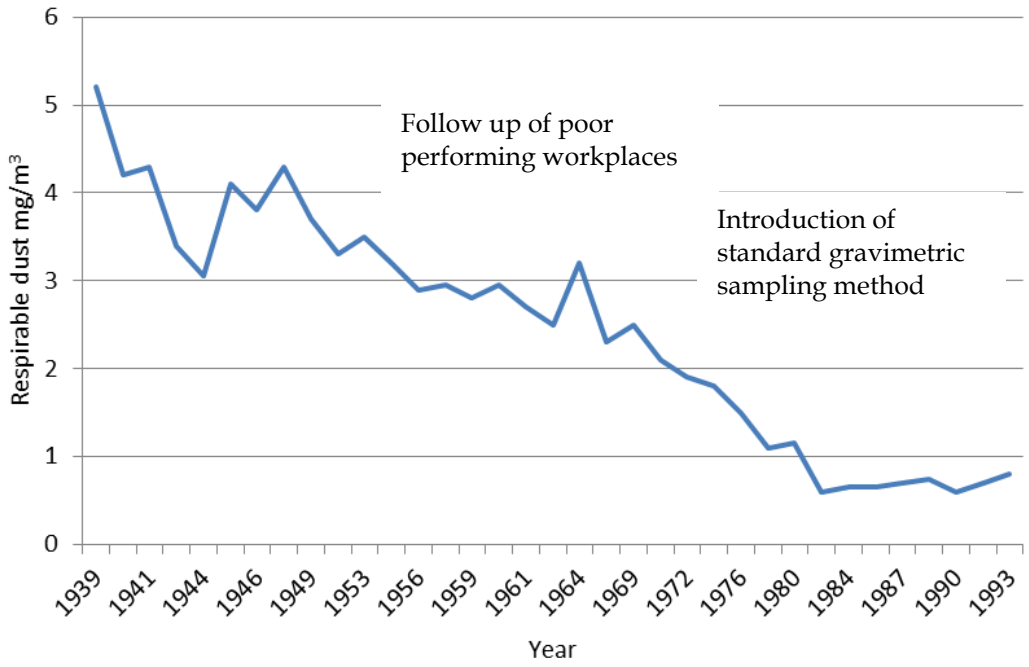


Figure 2.1: Estimates of mean respirable dust concentrations in Western Australian underground metalliferous mines (1939-1993). Pre-1979 data have been converted from konimeter count data using a factor of 1 mg/m³ per 100 particles per cubic centimetre (ppcc) (Source: Hewson 1996, p873)

Figure 2.2 uses the orignal data for particles per cubic centimetre (ppcc) converted to respirable dust in mg/m³ using the conversion factor: 1 mg/m³ per 100 ppcc.

The conversion factors applied between 1939 to 1975 are not clear. They questionable and need further qualification.

The modeled downward curve noted in Figure 2.1 is not shown in Figure 2.2, which uses actual (unadjusted) measurements in ppcc converted to mg/m^3 using the formula noted by Hewson (1996).

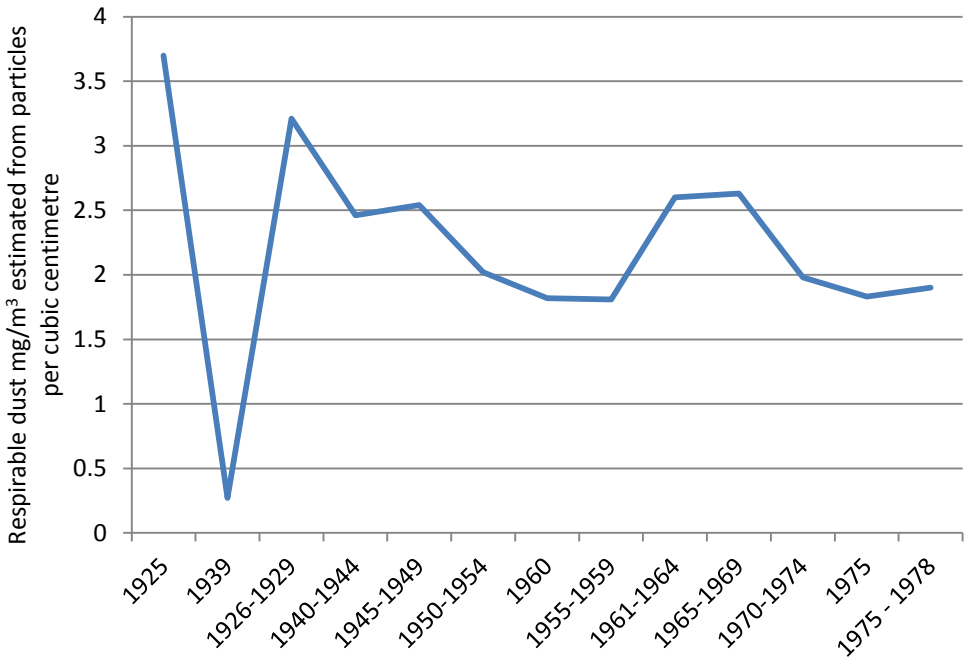


Figure 2.2: Mean estimated exposures in mg/m^3 of respirable dust in Western Australian underground metalliferous mines (1939-1993) using actual results in ppcc. (Hewson 1996, p.873).

Figures 2.3 and 2.4 show the results of tabulated RCS (quartz) concentrations for underground metalliferous mines for exposure results between 1979 and 1993 (Hewson 1996).

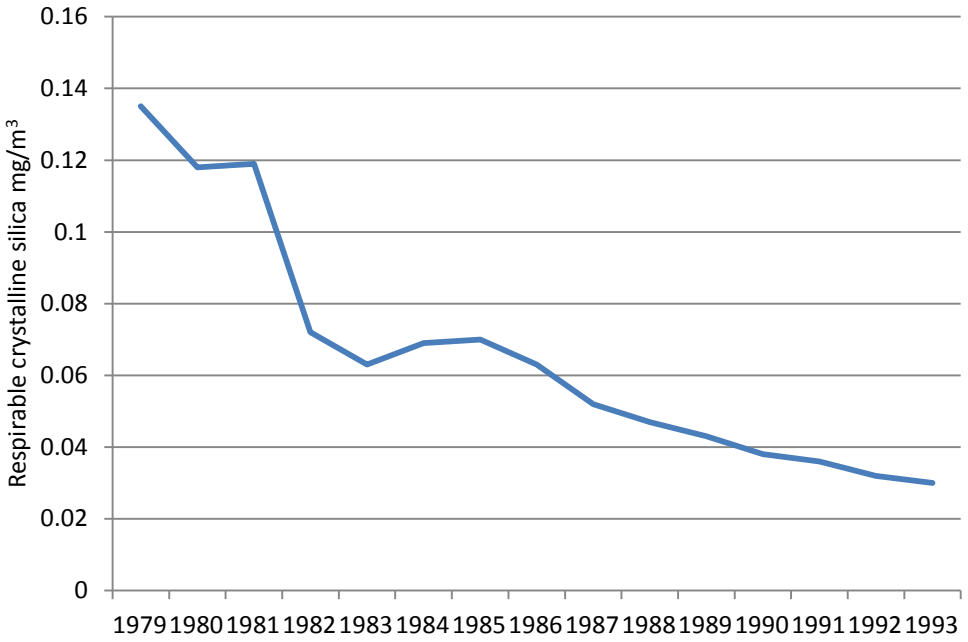


Figure 2.3: Geometric mean exposure of Western Australian miners to respirable silica in underground metalliferous mines in WA. (Hewson, 1996, p.873).

When (measured) RCS exposures are compared between 1979 and 1993, there is a reduction in geometric mean exposures (Figure 2.3). This is not the case when maximum exposures to RCS are graphed (Figure 2.4).

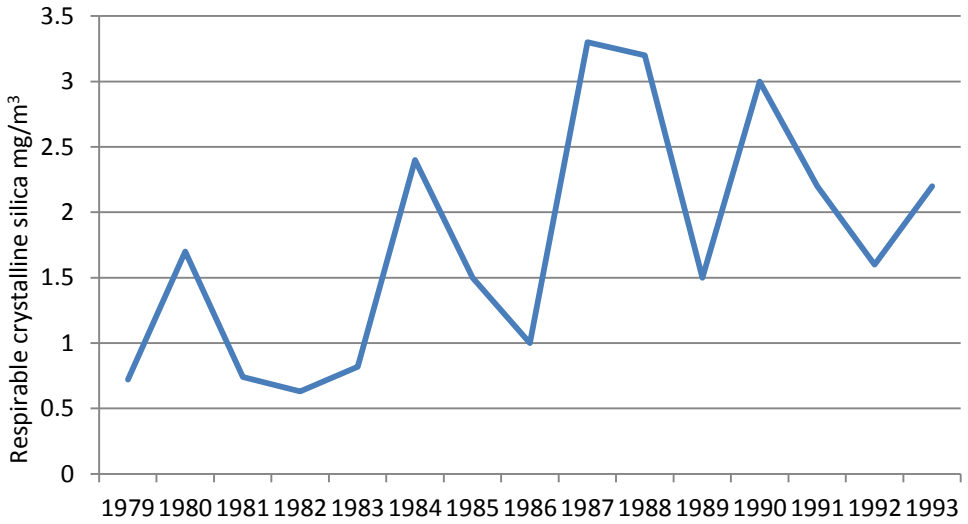


Figure 2.4: Maximum exposures to respirable silica in underground metalliferous mines in WA (Hewson 1996, p.873).

It is important to note that AS 2985 Workplace atmospheres – method for the sampling and determination of respirable dust was first published in 1984. This means that respirable dust measurements made prior to this may not have been measured in a consistent manner. Prior to 1984 there was no Australian standard.

Larcombe cited in Hewson (1996), referred to a study in the early 1900s where the mass of dust collected on the surface of respirators was used to indicate exposure. In that study it was estimated that inspirable dust concentrations typically exceeded 10 mg/m^3, and concentrations of 110 mg/m^3 were estimated for dry boring operations. Most cases of silicosis are likely to have been from workers performing high exposure tasks. Hewson (1996) suggested that the improvement in work conditions in the 1950s, resulting in lower dust exposures for most workers, was mostly attributed to the increased use of water sprays and improved ventilation.

2.1.1.2 USA Vermont Granite Workers

One of the most extensive studies published is the silica exposure assessment and mortality study of granite workers in Vermont, USA (Verma et al. 2010; Vacek et al. 2011). A job exposure matrix was developed using 5204 exposure measurements collected from 1924 to 2004. In that study, the percent of free silica (quartz) in respirable dust was estimated to be 11%. About 60% of all measurements made prior to 1972 were obtained using the impinger method which had a typical sampling time of 20 – 25 minutes (Verma et al. 2010).

NIOSH cited in Vacek et al. (2011) has recommended the use of a conversion factor of 10 million particles per cubic foot (mppcf) for equivalence to an RCS concentration of 0.1 mg/m^3. Verma et al. (2010) categorised similar exposure groups (SEGs) arbitrarily and it is difficult to know whether SEGs were indeed classified, grouped and validated by statistical analysis.

Further statistical analysis, on each of the similar exposure groups, will confirm whether SEGs have been categorized accurately.

From this dataset average exposures have been estimated for all job types combined for each period and reported along with maximum exposed job class as shown in Table 2.4.

Table 2.4: Estimated exposure concentrations of RCS by time period, for all job classes.
(Vacek et al, 2011 p.313).

Period	Estimated averages RCS mg/m^3	Maximum (exposed) job class RCS mg/m^3
<1940	0.16	1.07#
1940 - 1949	0.12	0.56##
≥1950	0.04	0.10###

Note: # Jackhammer; ## Jackhammer; ### Labourer

Vacek et al. (2011) used historical data collected using either a konimeter or impinger. The accuracy of the konimeter varied based on the type used, as discussed by Hewson (1996). In those studies results from short-term (grab) samples were used to estimate long-term average exposures. The accuracy of conversion of results from task based sampling to full shift time-weighted average measurements is likely to be low.

2.2 Health Effects

Silicosis is a fibrotic lung disease caused by the inhalation of RCS. It has been described as chronic silicosis (including simple and complicated silicosis), accelerated silicosis, and acute silicosis (Australian Institute of Occupational Hygienists (AIOH) 2009; ACOEM 2006).

The pathology of silicosis has been described as the presence of discrete, rounded and whorled hyalinised (glass-like) fibrous nodules that are sharply separated from the surrounding lung tissue. These nodules are more frequently reported with exposure to dusts containing more than 18% silica (Gibbs & Wagner 1998).

2.2.1 Chronic silicosis

Chronic silicosis is the most common form of silicosis, and results in fibrotic changes to the lungs after 10 to 30 years of exposure (AIOH 2009).

2.2.2 Simple silicosis

Simple silicosis, the usual form of chronic silicosis, is characterised by the presence of discrete rounded fibrous nodules in the lung. On the X-ray these are seen as 3 – 6 mm rounded opacities. Respiratory symptoms or lung function impairment may not be observed unless the person smokes or has coexistent disease. The fibrotic lesions in simple silicosis appear on the chest X-ray predominantly in the upper and middle lung zones as discrete small rounded opacities (AIOH 2009; ACOEM 2006).

2.2.3 Complicated silicosis

Complicated silicosis results when the silicotic nodules increase in size and coalesce into large lesions greater than 1 cm in diameter called progressive massive fibrosis (AIOH 2009). The conglomerate lesions may obliterate bronchi and blood vessels, and cause distortion of lung structure and function. Symptoms of workers with complicated silicosis range from chronic cough with phlegm production, to severe shortness of breath and rapidly occurring respiratory failure (AIOH 2009; ACOEM 2006).

2.2.4 Accelerated silicosis

Accelerated silicosis results from the inhalation of very high concentrations of silica dust over a period typically in the order of 5 to10 years (AIOH 2009). Although accelerated silicosis develops in a pattern similar to that of simple silicosis, the time from initial exposure to the onset of disease is shorter and the progression to complicated silicosis is more rapid (AIOH 2009; HSE 2010; ACOEM 2006).

2.2.5 Acute silicosis

Acute silicosis develops from the inhalation of high concentrations of RCS over a short period (7 months to 5 years) (AIOH 2009). The radiological appearance and the histopathological features are quite similar to those of pulmonary alveolar proteinosis. The radiological changes result from a filling of the air spaces by thick proteinaceous material (fluid and cells). Symptoms of acute silicosis include cough, weight loss, and fatigue. This may progress rapidly to respiratory failure over a period of several months. Death occurs after a few months. Acute silicosis has been reported among sand-blasters and drillers, and has historically been reported mainly among silica powder workers (AIOH 2009; ACOEM 2006).

2.2.6 Progressive massive fibrosis (PMF)

A condition called progressive massive fibrosis (PMF) can occur in silicosis or where there have been mixed dust exposures (AIOH 2005). When progressive massive fibrosis occurs, the patient develops progressive respiratory symptoms from reduction in lung volume, distortion of bronchi, and emphysema.

The main symptom is shortness of breath, which is progressive and ultimately disabling, potentially leading to cardio respiratory failure.

This has been well described in AIOH2005) and ACOEM 2006). Coal workers exposed to respirable quartz within coal dust may have lesions in the lung somewhere between a silicotic nodule and coal workers pneumoconiosis (CWP) nodule. The disease reported from this kind of lung nodule has been described as mixed dust pneumoconiosis. Fibrous tissue is observed along with enlarged lymph nodes (AIOH 2005).

2.2.7 Pulmonary tuberculosis

Silica particles can destroy or alter the function of the pulmonary macrophage, thereby reducing its capacity for defence (AIOH 2009). Occupational exposure

to silica dust renders a subject susceptible to developing pulmonary tuberculosis. Hnizdo & Murray (1998) reported that the risk of developing pulmonary tuberculosis while exposed, and also after exposure ended, depends on the cumulative amount of silica dust exposure. Hnizdo & Murray (1998) also noted that presence of silicosis in the lung further increased the risk of developing pulmonary tuberculosis, and that the rate of tuberculosis in workers exposed to silica dust is also related to the rate of tuberculosis in the general population.

2.2.8 Chronic obstructive pulmonary disease

There is a growing weight of evidence which demonstrates exposure to RCS causes COPD (Hnizdo & Vallyathan, 2003). COPD is also known by a number of other names including chronic obstructive airway disease (COAD), chronic airflow obstruction (CAO) and chronic airway limitation (CAL). COPD can also be referred to as chronic bronchitis and emphysema. COPD does not include asthma in which the airflow obstruction is largely reversible. Destruction of alveolar walls in silica dust exposed subjects can lead to emphysema which is the main cause of COPD. Emphysema develops primarily in subjects who smoke, but silica dust exposure greatly increases the damage from smoking. Thus, stopping smoking is the most important preventive measure for COPD in silica dust exposed workers (Hnizdo & Vallyathan 2003).

Korn cited in Driscoll et al. (2005, p.5) found that in developed countries:

'the relative risk for COPD is 1.0, 1.4 and 1.8 (controlled for smoking) which correlates with non-dust exposed, low exposure and high exposure respectively'.

Exposure concentrations aren't provided however, mine's working in developed countries is considered as a high dust exposed group.

The exact mechanism of dust exposure and COPD from the literature is uncertain. Examination of lungs of workers with occupational dust exposure shows airway fibrosis with thickening of the airway wall and narrowing and

distortion of airways. It has been suggested that the membranous bronchioles and respiratory bronchioles are points of high dust deposition. The respiratory bronchioles are the bridge between bronchioles and alveolar spaces and serve both air-conducting and gas exchange functions (HSE 2002; Hnizdo & Vallyathan 2003).

2.2.9 Lung cancer

In 1997, a monograph published by IARC concluded that there is now sufficient evidence in humans confirming the carcinogenicity of inhaled crystalline silica in the form of quartz or cristobalite from occupational sources (IARC 1997). Several studies among the many reviewed by the IARC working group found that silica exposure and cancer risk in humans was negative. However, nine studies showed an excessive risk for lung cancer. These included refractory brick workers, pottery workers, diatomaceous earth workers, foundry workers, granite workers, and mine workers but not coal-mine workers. The relationship between the ability of silica to generate free radicals (reactive oxidative species) and carcinogenesis is now confirmed (Castranova & Vallyathan 2000).

The IARC (2012, p.378) states that:

> 'The industries with the least potential for confounding are sand gravel operations, quarries and diatomaceous earth facilities'.

From a study of ten cohorts from various industries and countries,

> 'All indices of cumulative crystalline silica exposure showed highly significant trends with lung cancer risk ($p<0.0001$), and average exposure demonstrated a less significant trend ($p<0.05$) (Steenland cited in IARC 2012, p.376).

IARC (2012, p.374) also referred to a case-control study of sand and gravel workers who had worked 6 or more months. A dose response correlation was

found using quartiles of cumulative exposure (p=0.04) and increased significance with average exposure (p=0.003).

The National Toxicology Program (NTP) cited in Steenland & Ward, (2014, p.67) determined that:

> 'crystalline silica was a human carcinogen in 2000, and reaffirmed this position in 2011'

The IARC (2012) qualified their position and further confirmed that exposure to quartz or cristobalite does in fact cause lung cancer for smokers, former smokers and for never smokers (IARC 2012, p.377).

Liu et al, (2013, p.1) investigated a cohort of 34,018 workers in China and reported a trend that demonstrated a dose response relationship between lung cancer and exposure to crystalline silica for workers without silicosis.

Liu et al, (2013, p.1) also provided a quantitative risk estimate for workers exposed from 20 – 65 years at 0.1 mg/m^3 RCS which is the SWA-ES:

> 'the estimated lifetime risk (through 75 years) was 0.51% (95% CI 0.34%, 0.68%)'.

Liu et al, (2013, p.3) also noted that:

> 'The exposure level should be under 0.04mg/m3 to keep the excess lifetime risk within 0.1%'

Steenland & Ward (2014, p.64) state that:

> 'There is strong evidence that silica causes silicosis and lung cancer

Steenland & Ward (2014, p.68) refers to an excess lung cancer risk for the general population at about 6% by age 85 years or 60/1000). Steenland and Ward (2014, p.68) also refers to

'OSHA's goal of no more than 0.1% or 1/1000 excess risk, which equates to no more than 61/1000'.

2.2.10 Non respiratory health impacts

Increased risk of renal disease has been implicated with elevated exposures to RCS. A recent US study found a doubling of risk of non-malignant renal disease but no increase in renal cancer in a cohort of industrial sand workers (McDonald et al. 2005).

IARC (2012, p.378) cited a study by Attfield & Costello where it was noted:

> 'kidney cancers increased with increasing exposure'.

Steenland & Ward (2014, p.64) provided an overview of the literature by stating that there is:

> `suggestive evidence that it causes renal disease, and limited evidence that it causes autoimmune diseases, particularly scleroderma and rheumatoid arthritis'.

Lee et al. (2014), on the other hand, note that there are autoimmune disorders brought on by silicosis which include rheumatoid arthritis, systematic lupus erythematosus, and systematic sclerosis. This is confirmed by Chauhan et al. (2006), where these immunologists believe that there is in fact considerable evidence that there is an association between silica dust (quartz) exposure and the same autoimmune diseases mentioned above.

2.3 Exposure and risk

2.3.1 Dose response relationships between exposure and disease.

2.3.1.1 Western Australia.

In the study of Western Australian miners, Hewson (1996) reported the incidence of silicosis since 1925 (Figure 2.5). A new silicosis case is one defined previously as normal but on re-examination indicated early silicosis (>ILO

classification 1 / O). The X-rays were read by independent respiratory physicians employed by the Western Australian health department (Hewson, 1996).

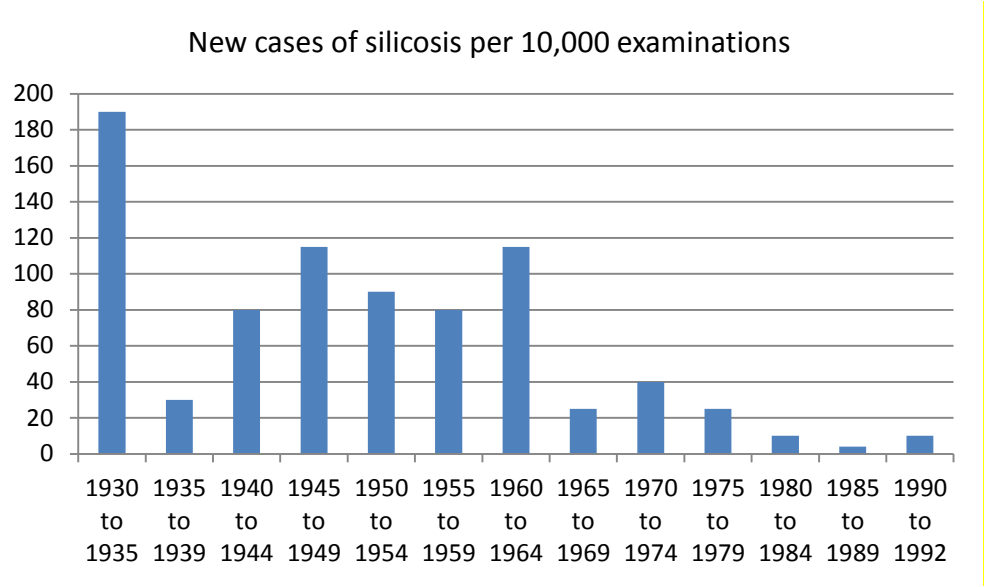


Figure 2.5: Incidence of new cases of silicosis following X-ray re-examination of Western Australian metalliferous miners from 1925 to 1992. (Hewson 1996, p.875).

Most cases of silicosis are likely to occur in workers performing tasks with high exposure to RCS. Buchanan, Miller & Soutar (2003) noted that quantifying the risk of silicosis should take into account the variations of quartz exposure intensity, particularly for exposure to concentrations of greater than 1 mg/m^3, even if exposure is for relatively short periods. These authors also implied that the risk of silicosis rises dramatically with brief exposures to high quartz concentrations.

2.3.1.2 Vermont Granite Workers.

Vacek et al. (2011) studied mortality records for 7052 workers employed in the granite industry in Vermont USA from 1947 to 1948. In that study, no significant link was shown between low level exposure to airborne silica and lung cancer, but there was a reported odds ratio (OR) of 1.13 (1.05 to 1.21) for silicosis for each 1 mg/m^3.year increase in cumulative exposure to RCS. This equated to exposures of 0.1 mg/m^3 for 10 years or 0.05 mg/m^3 for 20 years.

Although an increased risk for long term exposure was estimated for <0.1 mg/m^3 for 55 cases where death resulted from silicosis, only 6 began work after 1940, and 3 began work after 1949. Hence they worked for less than 10 years in the Vermont granite industry (Vacek et al. 2011). Using mortality records to examine a relationship between silica exposure and silicosis is questionable because the number of workers affected from low level exposure (during their lifetime) was not established. Vacek et al. (2011) did not provide any analysis where RCS exposure for each job-type was compared with mortality from selected diseases. Reassessing the historical data and comparing the level of pooled exposure for each SEG with mortality from disease will be worthwhile. This will allow statistical analysis across all SEGs and grouping of workers where the nature of exposure, including particle size distribution, would be similar. Such analysis may improve how dose response assessment is undertaken and identify SEGs that have an increased risk of disease. Chest x-rays were investigated in 1983 to determine whether low level granite dust exposure could lead to lung abnormalities after a lifetime exposure to dust containing silica (Graham et al. 1991). Workers who had been exposed to dust from 1938 to 1940 were assessed. In that study 972 out of 1,400 chest x-rays were read by 3 "B" readers using the ILO classification system. Of these, 28 (3%) were interpreted as showing (1/0) pneumoconiosis and 7 (0.7%) showed uncomplicated silicosis. For those remaining - 21 showed irregular opacities, which were reported as having uncertain significance. The average RCS concentration was estimated to be 0.06 mg/m^3, with 12% exceeding 0.1 mg/m^3 (Graham et al. 2001). In that study, years worked in the industry ranged from 9 to 60. Many of the chest x-rays were irregular and interpretation varied between readers. The estimated exposure to RCS for the 0.7% of workers diagnosed to have (1/0) silicosis was 0.06 mg/m^3. This reported risk generally agrees with a similar Scottish study which estimated that an exposure of 0.04 mg/m^3 for 15 years resulted in an increased silicosis (2/1) risk of 0.5% (HSE 2002). Graham et al. (1994) examined lung function where exposures were below 0.1 mg/m^3. After adjusting for variables such as age, height and smoking status, the

assessment failed to demonstrate a relationship between low level silica exposure and loss of lung function.

2.3.1.3 Tunnel workers.

In a study of tunnel workers Ulvestad et al. (2001), it was noted that lung function would have been affected by smoking. At low exposures to respirable quartz (0.02 mg/m^3 to 0.04 mg/m^3), an annual decrement of FEV_1 of 50 to 63 mL was observed. Gamble, Hessel and Nicolich (2004) noted that smoking must always be considered, as adverse changes in lung function have been attributed to smoking. This means that all studies of lung function will be biased if workers who smoke are not considered. A relationship between smoking and radiographic opacities has been reported which means that this factor is not independent of RCS exposure and pneumoconiosis (Hessel, Gamble & Nicolich 2003). There is an association between loss of lung function, smoking, and dust exposure, and increased loss of lung function with higher categories of silicosis (Gamble, Hessel & Nicolich 2004). It was also found that tunnel workers had an increased odds ratio (OR) for respiratory symptoms, during the follow-up period, which was associated with cumulative exposure to respirable dust (Ulvestad et al. 2001).

2.3.1.4 Ontario Miners.

Muir et al. (1989) examined x-rays from 2109 Ontario miner's which were read by 5 "B" readers. Of the 32 cases of 1/1+ silicosis identified, years since first exposure and age at diagnosis was recorded. Where 3 or more readers agreed on the classification, the case was confirmed and allocated into an exposure band which was based on historical exposure data (Table 2.5). Table 2.5 demonstrates the importance of having more than one "B" reader classify chest x-rays, and conducting health surveillance many years after exposure (Muir et al. 1989). For example, reader one only confirmed 14 cases of silicosis, whereas reader two confirmed 24 cases. In other words, if only one reader assessed the x-rays, it is evident that a number of cases may in fact, not be diagnosed. It is

also suprising that of the five B readers, there was agreement on only 6 of the x-rays confirmed to be silicosis.

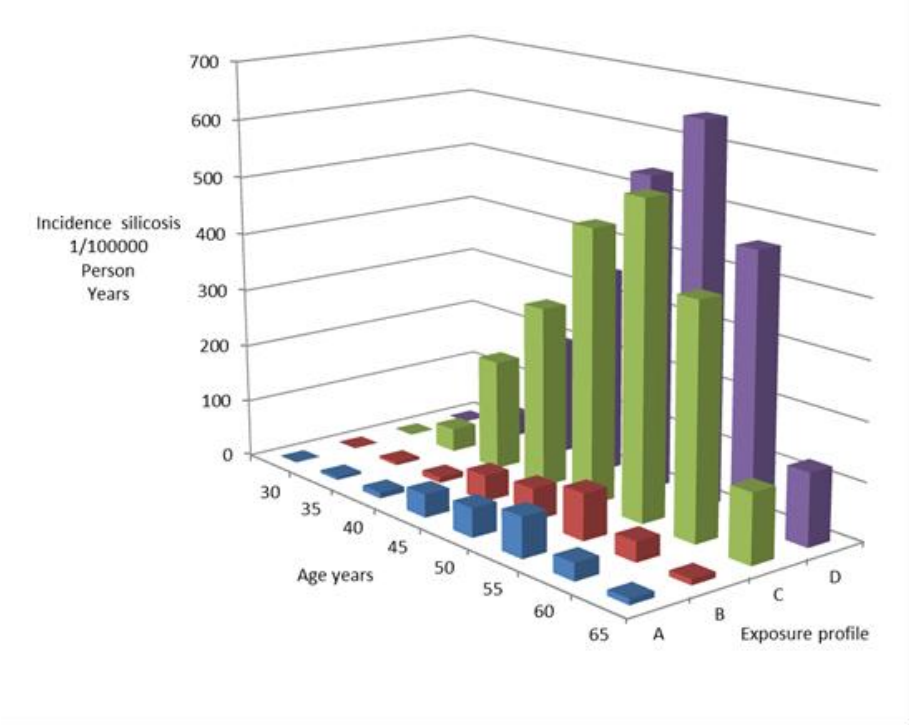
Table 2.5: Cumulative Risk Estimates (Percent) of Developing Silicosis and 95% Confidence Intervals for Four Levels of Mean Respirable Exposure (mg/m³) by Reader(s), based on 40 years exposure (Muir et al, 1989, p.40).

	Mean RCS exposure (mg/m³)				
X-ray Reader	Number of cases of silicosis from X-rays	0.05	0.10	0.15	0.20
	Cumulative risk estimate (percent) of developing silicosis (95% confidence intervals)				
1	14	0.5 (0.2 - 0.9)	1.2 (0.7-2.1)	2.1 (1.3 - 3.6)	3.2 (1.8 - 5.7)
2	24	0.6 (0.3 - 1.1)	2.0 (1.3 - 3.0)	3.8 (2.6 - 5.6)	6.1 (4.0 - 9.3)
3	24	0.5 (0.2-0.9)	1.8 (1.1 - 2.8)	3.9 (2.6 - 5.7)	6.7 (4.4 - 10.0)
4	14	0.4 (0.2 - 0.8)	1.1(0.7 - 2.0)	2.2 (1.3 - 3.8)	3.6 (2.0 - 6.3)
5	7	0.1 (0.0 - 0.4)	0.5 (0.2-1.1)	1.1 (0.5 - 2.4)	2.1(1.0 - 4.5)
Any reader	32	0.9 (0.6-1.5)	2.7 (1.9 - 3.8)	5.0 (3.5 - 7.0)	7.7 (5.3-11.1)
Majority 3 or more	15	0.4 (0.2 - 0.8)	1.2 (0.7 - 2.1)	2.4 (1.4 - 3.9)	3.8 (2.2 - 6.5)
All readers	6	0.1 (0.0 - 0.4)	0.4 (0.2 - 1.1)	1.0 (0.4 - 2.2)	1.0 (0.4 - 2.2)

2.3.1.5 Chinese pottery workers.

Sun et al. (2011) in their study of 3250 Chinese pottery workers estimated the exposure response relationship between RCS and the incidence of category 1/1 silicosis for workers until the age of 65. The follow up period was approximately 37 years. This study differed from previous studies in that both long term average concentrations were estimated as well as the highest annual concentration and the time since initial exposure. The risk of silicosis was 1.5 /1,000 (0.15%) for workers with a long term average exposure < 0.1 mg/m³. This risk is greatly compounded when the long term average is coupled with a maximum annual average > 0.1 mg/m³. Figure 2.6 notes age, for Chinese pottery workers, when silicosis is diagnosed and also compares exposure profiles for each exposure type, as provided in the legend. These results challenge the findings from previous studies Meijer et al. (2001) and Ulvestad et

al. (2001), which indicated that the risk of contracting silicosis is higher with cumulative RCS exposure based on a time weighted average long-term exposure typically reported as mg/m^3 years.



Exposure profile - legend

Code	Exposure profile
A	Average ≤ 0.05 mg/m^3; Maximum annual average ≤ 0.05 mg/m^3
B	Average 0.05 – 0.1 mg/m^3; Maximum annual average ≤ 0.1 mg/m^3
C	Average 0.05 – 0.1 mg/m^3; Maximum annual average 0.1 – 0.5 mg/m^3
D	Average 0.1 – 0.15 mg/m^3; Maximum annual average 0.1 – 0.5 mg/m^3

Figure 2.6: Incidence of silicosis in Chinese pottery workers, showing estimates of exposure and the age at which silicosis was determined.
(Adapted from Sun et al. 2011, p.2931.)

Figure 2.7 notes different risk profiles and a comparison can be made of the different excess risk of silicosis per 1000. What is immediately obvious is the step change in risk for exposures between 0.1 – 0.5 mg/m^3.

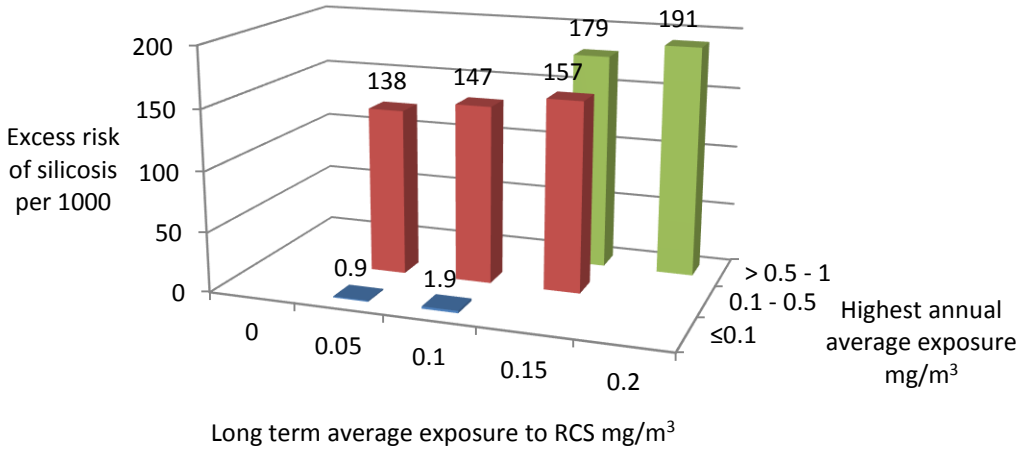


Figure 2.7: Chinese pottery workers excess risk of silicosis, comparing long term average exposure with higher annual exposures
(Adapted from Sun et al. 2011, p.2931).

It is apparent from Figures 2.6 & 2.7 that low long term average exposures with a relatively lower maximum annual exposure (over a lifetime), 0.05 – 0.1 and < 0.1 respectively, have a lower risk of silicosis compared with lower average exposures coupled with higher maximum annual exposure of 0.05 – 0.1 and 0.1 – 0.5 respectively.

2.3.1.6 United Kingdom Quarry workers.

The United Kingdom (UK) Health and Safety Laboratory (HSL) carried out a silica baseline survey for a number of industries, including the quarry industry (HSL 2009). The study found that 10 of the 61 measurements exceeded the workplace exposure limit (WEL) of 0.1 mg/m^3. The survey made no mention about loss of lung function in quarry workers.

2.3.1.7 New Zealand Extractive Industry.

Respiratory health and silica dust levels were assessed as part of a New Zealand national dust project during 1995 to 1999. The report for this assessment noted 13% of worksites sampled for dust had levels of RCS in excess of the New Zealand work place exposure limit time weighted average of 0.2 mg/m3 RCS. In the New Zealand study, FEV1 and FVC were also measured. That study also showed that a reduction in the mean expiratory flow correlated

with increased years of exposure to dust and RCS among non-smoking quarry workers (Glass et al. 2003).

2.4 Mechanism of toxicity

There is general agreement that freshly fractured crystalline silica particles are more toxic than aged surfaces as demonstrated by in-vitro tests conducted in animal studies (HSE 2002). The crushing of crystalline silica can result in breakage of the Si-Si and Si-OH bonds at the surface. This results in the formation of reactive radicals at the particle surface. These species are highly reactive and through cellular activation resulting in superoxide, hydrogen peroxide and nitric oxide. The formation of reactive oxidative species (ROS) is damaging to cell DNA. Superoxide can also react rapidly with nitric acid to form peroxynitrite, an agent that oxidizes and nitrates macromolecules. Studies also indicate that reactive nitrogen species (RNS) are released from affected alveolar macrophages (Brooke & Mossman 1998). One model of this pathway can be seen in Figure 2.8.

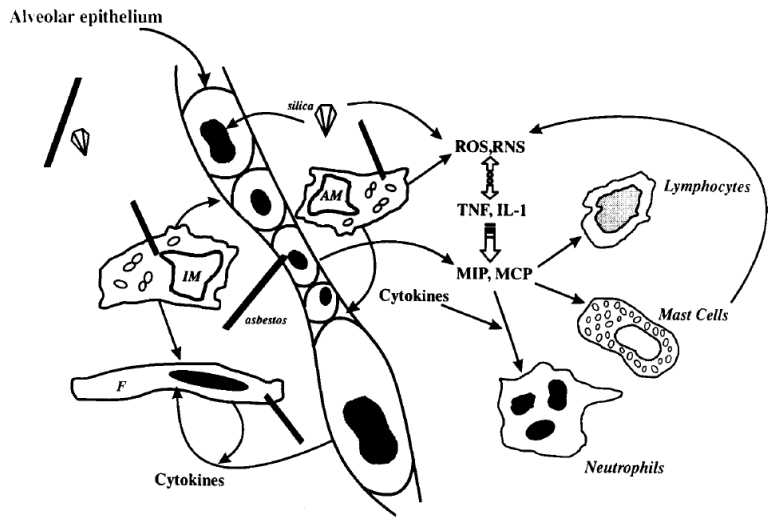


Figure 2.8: A conceptual model of events occurring in the lung following exposure to pathogenic mineral dusts
(Source: Brooke & Mossman 1998, p.1674).

The HSE (2002) note: that the activity of free radicals decays with ageing (time), and occurs slowly in air, but rapidly in water. Wet-processes that quench

freshly cut quartz will help reduce this reactivity. Metal contaminants may either exacerbate the potential for silicosis or provide a protective mechanism. Driscoll cited in HSE (2002) noted that iron contamination can potentially increase the toxicity of silica by catalysing the production of reactive oxygen species as shown in Figure 2.8. Fenton's reaction shows how iron can catalyse the production of hydroxyl species (ROS) which is an initial contributor leading to silicosis. Aluminium on the other hand has been suggested as providing a protective layer (HSE 2002). Fenton's reaction is shown by the following formulae:

$$Fe^{2+} + H_2O_2 \text{ ----> } Fe^{3+} + .OH + OH^-$$

$$Fe^{3+} + H_2O_2 \text{ ----> } Fe^{2+} + .OOH + H^+$$

Studies in rats and sheep have demonstrated that pulmonary inflammation is reduced by aluminium. The presence of aluminium in coal mines for instance has been used as justification that crystalline silica is less toxic in this environment. Research has challenged this notion by showing that the protective effect is transient and over time the protective effect is lost as aluminium is removed from the silica surface (HSE 2002).

2.5 Particle size sampling convention.

Definitions of three health related aerosol fractions (inhalable, thoracic and respirable) were proposed by Soderholm (1989) and adopted by EN (1993), ISO (1995) and the ACGIH (1994) (Vincent 2005). This broad international agreement aligns previous definitions into a single world-wide convention (Vincent 2007). As the target organ for crystalline silica is the lung, RCS is sampled. RCS is the fraction of airborne dust that is sampled using a miniature cyclone device. In other words, the cyclone sampling device collects the airborne dust particles of a size distribution ≤ 10 μm which will penetrate the lower airways including un-ciliated alveoli (Vincent 2005).

The health-related aerosol fractions defined, relate to the probability of penetration of airborne particles to the various anatomical regions of the

respiratory system and provide a specification for the performance of sampling instruments (see Figure 2.9). The inhalable convention is the mass fraction of total airborne particles that enters the nose or mouth during breathing, The thoracic convention is the mass fraction of inhaled particles that penetrate the larynx, with 50% penetration at 11.64 µm (equivalent to 10 µm when expressed as a fraction of total aerosol). The respirable convention is the fraction of inhaled particles that penetrate to the alveolar region of the lung, with 50% penetration at 4.25 µm (equivalent to 4 µm when expressed as a fraction of total aerosol) (ISO 1995).

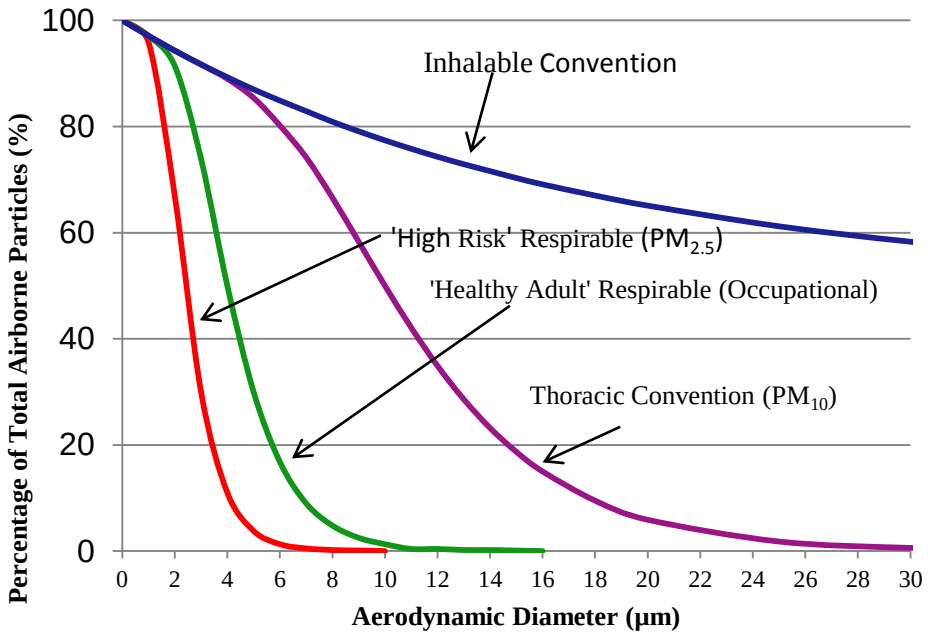


Figure 2.9: Particle size distributions and collection efficiency curves according to ISO, 7708 1995 (Adapted from: ISO 1995, p7)

The physical nature of silica in respirable dust and its impact on lung health is important. Vincent (2012) cites Fuchs, who proposed that the particle will have the same gravitational settling speed in air: must consider density, shape and inertial forces leading to impaction. Vincent (2012) noted that the deposition of particles greater than 0.5 µm takes place by a combination of inertial (impaction) and gravitational forces. Based on research using a horizontal

elutriator, criterion has developed that mimics how particles penetrate the lung. This theory has been further translated from using a horizontal elutriator to a personal sampling cyclone. The curve starts at 100% for very small particles and has a 50% cut point or assigned median equivalent aerodynamic diameter (EAD) of 4.25 μm.

Vincent (2012, p. 343) states that pneumoconiosis historically is:

> 'Clearly associated with aerosol exposures based on the new respirable mass index, and limit values – aimed at achieving acceptable levels of disease were developed'.

Cyclone personal sampling technology is based on particle aerodynamic diameter, particle shape (for a sphere), density and inertial impact. Particle Equivalent Aerodynamic Diameter (EAD) is defined as the diameter of a 1 g/cm^3 density sphere having the same settling velocity as the particle in question. Non spherical shaped, different roughness and density particles may orient differently and have different settling velocities (Isabella, Glossop & Green 2004). Inertial impact plays an important part in collection efficiency and particle behaviour in the respiratory tract (Isabella, Glossop & Green 2004). In discussions on cyclone personal sampling technology Abdel-Salem (2006, p.444) described cyclone samplers as using centrifugal forces for particle separation and provided a schematic on their mode of action (Figure 2.14).

Figure 2.10 provides an illustration of how air circulation occurs inside the cyclone, and how sampled air containing the larger particles is directed to the outside of the cylinder and then into the conical section.

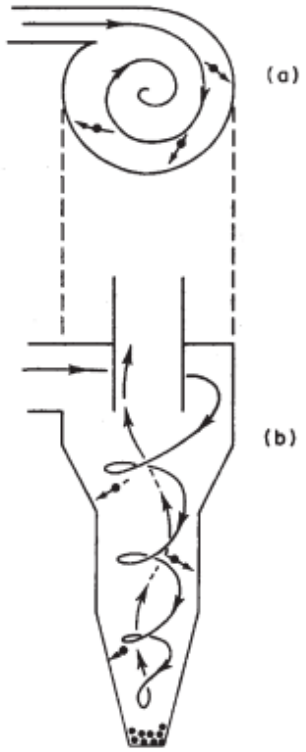


Figure 2.10 Schematic to show air and particle size motion in a cyclone (a: plan view, b: side view) (Abdel-Salem 2006, p.444).

The larger, denser particles resist being entrained in the air-flow and impact onto the cyclone wall. These larger particles then migrate down the cone shown in Figure 2.10 and into the grit pot. Particles that are smaller remain entrained in the upward circulating air and are deposited on the filter. The collection efficiency depends on the EAD. The fraction of sample size collected particles is governed by the flow rate, the size of the inlet and outlet tubes, air velocity and size of the cylinder (Hering 1995; Abdel-Salem 2006). Air is withdrawn from the side and moved in rapid circular motion towards the bottom chamber of the cyclone. Separation of the particles is performed based on the density and weight of the particles, relative to the speed of the circulation. The conventional design of a cyclone sampling head used in Australia can be seen in Figure 2.11.

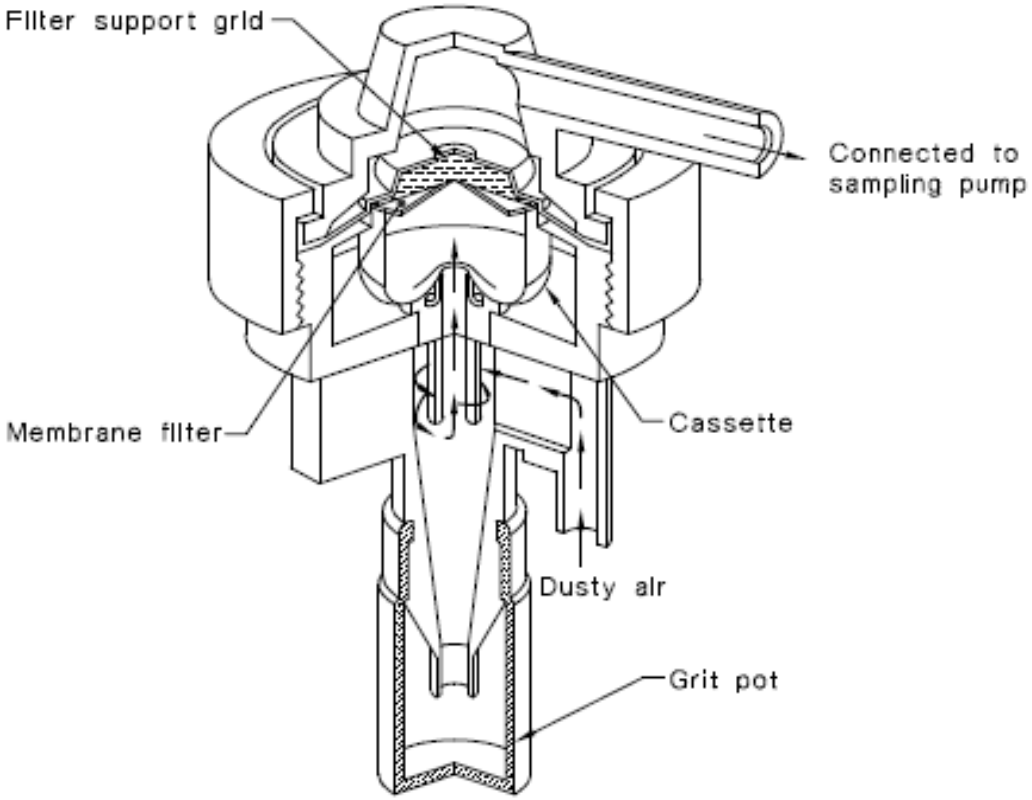


Figure 2.11 Schematic of a type of respirable cyclone used in Australian Mines (Source: Standards Australia, AS 2985-2009, p.8)

The sampling efficiency is defined by the penetration efficiency of particles as a function of particle aerodynamic diameter. Conventional penetration efficiency (sampling) curves were proposed for size-selective sampling by the BMRC (Walton et al. 1998). The BMRC definition of the respirable aerosol fraction was recognized internationally (Vincent 2007). Conventions for size-selective aerosol sampling have now been harmonized world-wide.

In 2004, AS 2985-2004 adopted the ISO 7708 - 1995 sampling curve (Table 2.6).

Table 2.6 Sampling efficiency curve for the cyclone sampler which conforms with the Australian standard for respirable dust.
(Standards Australia AS 2985-2009, p.6).

Particle Aerodynamic Diameter (μm)	Respirable Dust Fraction (ISO 7708) (%)
0	100
1	100
2	97
3	80
4	56
5	34
6	20
7	11
8	6
10	2
12	0.5
14	0.2
16	0.1
18	0

Prior to this, AS 2985 followed the BMRC sampling curve with a 50% cut in the efficiency collection of 5.0 μm (D_{50} = 5.0 μm) and a sampling flow-rate of 1.9 L/min. So that the Australian Standard AS 2985 - 2004 could align with the ISO 7708-1995 curve, which is 50% cut in the collection efficiency of 4.0 μm (D_{50} = 4.0 μm), the flow-rate was increased from 1.9 L/min to 2.2 L/min. It must be emphasized however that the correct flow rate depends on the type of cyclone sampler being used. The standard describes respirable dust as the proportion of airborne particulate matter that penetrates to the un-ciliated airways when inhaled. This fraction is further described in ISO (1995) as the percentage of inhalable matter collected by a device conforming to a sampling efficiency curve that passes through the points as previously seen in Figure 2.9.

Alternatively, it can be described by:

> 'a cumulative log-normal distribution with a median EAD (EAD) of 4.25 μm and a geometric standard deviation of 1.5 μm' (Standards Australia 2009, p.6).

Historically, the degree of respirability is estimated in terms of its EAD.

The aerodynamic diameter may be misrepresented using stokes law, which is for a spherical particle and far from may be typical particle morphology in mining. The true aerodynamic diameter depends on many factors such as:

- particle surface,
- size,
- shape,
- electrostatic properties,
- hygroscopic properties, and
- ability to aggregate, (Hassan & Lau 2009)

Elongated or needle-like particles are reported to have longer suspended time in the air and can travel further in the long airway (Larhrib et al. cited in Hassan & Lau 2009, p. 1252).

Although the Australian Standard (SA (2009, p.6), defines respirable dust as:

> 'the proportion of airborne particulate matter that penetrates to the unciliated aiways when inhaled';

the science is based on information that is at least twenty years old (ISO 1995). In fact there are different sub-fractions within the respirable dust size range that vary in toxicity, with distinct adverse health effects to the lung. The respirable dust sampling convention is not explicit in explaining the importance of particle shape. Particle shape has been shown to have a major effect on particle behavior (Hassan & Lau, 2009) in breathing air and in the lung.

2.6 Particle size that reaches the alveolar region of the lung.

Figure 2.12 shows that particles smaller than 2.5 µm reach the alveolar duct whereas particles greater than this are cleared by muco-ciliary clearance.

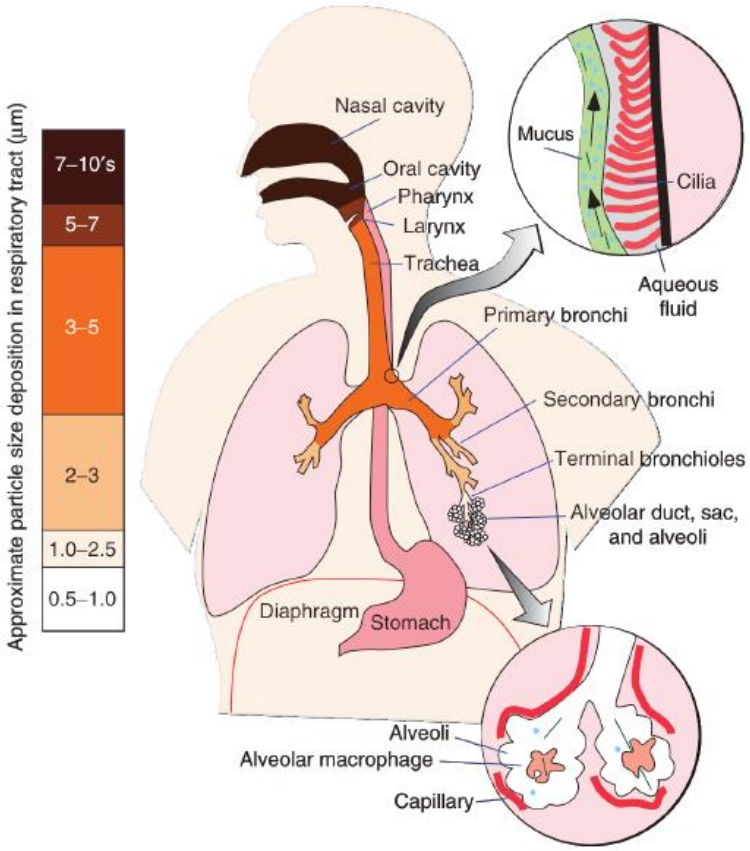


Figure 2.12: A schematic representation of the respiratory tract showing details of the alveolus and of the muco-ciliary clearance. The colours from brown to pink show the particle size distribution in the respiratory tract (Plumlee & Ziegler 2006, p.276).

According to Kerr, Vincent & Ramachandran (2001) the assessment of the true health-related dose received by a worker, possibly leading to ill-health from inhalation, requires full characterization of the aerosol as a function of particle size distribution and chemical species.

Vincent (2005) reported that some occupational health experts have expressed concerns about fine particles and ultra-fine particulate aerosols in the workplace environment.

This is an important point as it is generally assumed that silicosis is caused by the fraction of silica that reaches the alveoli (Office of the Environmental Health Hazard Assessment 2005; King et al. 1953). Kysela et al. (1973) showed that evaluating the different sub-fractions, within the respirable dust size range, is important based on their study on rats which demonstrated a statistically high potency of inhaled quartz dust with a physical diameter less than 5µm. They also found the highest fibrogenic response seen was for particles less than 1µm. Nodules were observed in the lungs of the rats which are indicative of early silicosis. This was also seen in the lungs of rats exposed to particles with a particle diameter of 3 to 5µm. Any effects for rats exposed to quartz dust with a diameter > 5µm was significantly lower (Kysela et al. 1973). Kysela et al. (1973) does not discuss particle shape. Conversely, Weissner et al. (1989) observed that relatively larger particles ≥5 µm were more fibrogenic than 1 µm particles. Notwithstanding, the more recent literature suggests that total surface area is more important than mass. As the particle numbers increase so does the surface area of affected lung tissue. Many smaller particles will have a greater surface area than fewer larger particles (HSE 2002). Fine particles also have much longer residence times than coarse particles which mean that airborne fine particles will stay airborne for much longer periods than larger particles, leading to a greater likelihood to inhale fine particles. Exposure to excessive numbers of fine particles may also overwhelm the ability of alveolar macrophages to engulf and remove foreign particles. According to Girod, Talmage & King (2007), the chronic characteristic of COPD is caused by a mixture of small airway disease (obstructive bronchiolitis) and parenchymal destruction (emphysema). Historically, the disease that has received the most attention from silica exposure is silicosis; the target area being the deep lung's alveolar region where gas exchange takes place.

Central to the establishment of a sampling standard, the term EAD, has been a central reference for many years. Standards Australia, (2009 p.6), defines EAD as:

> 'the diameter of a particle of unit density (1g/cm^3) that exhibits the same aerodynamic behavior as the particle in question'.

An improved risk characterization profile is still required for epidemiological requirements and method development. The use of AS2985-2009 alone, will not allow this characterization. Analysis by Electron Microscopy (EM) provides more comprehensive information for assessment.

The American College of Chest Physician's Committee on Occupational Diseases of the Chest cited in Kysela et al. (1973, p. 103) noted that:

> 'quartz particles less than 10 μm are virtually harmless, particles of 1 - 3μm produce a typical silicosis and particles < 1 μm may give rise to dangerous atypical silicosis'.

Brieger; King et al. Goldstein & Webster cited in Kysela et al. (1973, p. 103) confirmed the silicogenic effect of quartz dust as 5 – 0.5 μm. This is consistent with Lindstrom (2004), who notes that smaller particles 0.5 – 3 μm are deposited in the terminal airways and in the alveolar region. Dimensions of the small airways in human lungs are shown in Table 2.7. Particles larger than 10 μm are deposited in the upper airways. Particles 3 – 10 μm are deposited in the trachea and larger airways due to impaction. Smaller particles 0.5 – 3 μm are deposited in the terminal airways and in the alveolar region. Ultrafine particles less than 100 nm are deposited in the alveolar region and a larger percentage is exhaled (Lindstrom 2004). Current methods of sampling for respirable dust may over-sample the dust fraction that is responsible for lung disease. Respirable dust sampling collects both the particle size fraction responsible for COPD and particles >3 μm. PM2.5 may provide a better indication of the risk when attempting to identify a dose response relationship.

Table 2.7: Dimension of human airway model.
(Weibel 1963, cited in Lindstrom 2004, p.10).

Anatomical structure		Generation	Number per generation	Mean diameter (cm)	Mean length (cm)	Cross sectional area (cm^2)
Trachea Main bronchi Lobar bronchi Segmental bronchi Sub-segmental bronchi	LARGE AIRWAYS	0	1	1.80	12	2.54
		1	2	1.22	4.8	2.33
		2	4	0.83	1.9	2.13
		3	8	0.56	0.76	2.00
		4	16	0.45	1.27	2.48
		5	32	0.35	1.07	3.11
		6	64	0.28	0.90	3.94
		7	128	0.23	0.76	5.31
		8	256	0.186	0.64	6.95
Terminal bronchi Bronchioles	SMALL AIRWAYS	9	512	0.154	0.54	9.53
		10	1024	0.130	0.46	13.6
		11	2048	0.109	0.39	19.1
		12	4096	0.095	0.33	29.0
		13	8192	0.082	0.27	43.2
		14	16384	0.074	0.23	70.4
		15	32768	0.066	0.20	112
Terminal bronchioles Respiratory bronchioles Alveolar ducts Alveolar sacs	ACINUS*	16	65536	0.060	0.165	185
		17	131907	0.054	0.141	300
		18	262144	0.050	0.117	534
		19	524288	0.047	0.099	944
		20	1489576	0.045	0.083	1600
		21 - 23	15000000	0.042	0.060	~ $140m^2$

* Note - acinus is the anatomical name for the cluster of alveolar sacs.

More recently there has been a focus by the ISO and European Committee for Standardisation (CEN) to investigate particle deposition in specific areas of the respiratory tract (Bartley & Vincent, 2011). The science is still emerging. For health-risk based exposure measurement and index of exposure, it is widely accepted that particulate matter surface area, not mass, is the most appropriate measure (Vincent, 2012). Both particle size and shape, jointly determine the surface area of a particle, and hence are important for cellular effects. Cytotoxic potential exists for smaller particles because they have a larger surface area per unit mass (Michel et al. 2014).

Exposure time of the particles reactive surface to the membrane, and DNA, has also been implicated to result in oxidative and genotoxic stress, leading to fibrosis and cancer (Fanizza et al. 2006). Therefore particle surface area and shape must be considered in the sampling convention.

2.7 Particle shape

The crystal system of alpha quartz is trigonal (Dutch 2002) (Photo 2.1) and the basic structure of quartz consists of spiral chains (helices) (Lavinsky 2003). The image (Figure 2.13) of quartz by Lavinsky (2003) represents the alignment of the screw axes with three-fold connected into a framework.

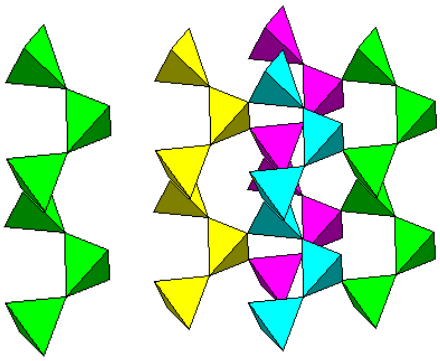


Figure 2.13: Model showing three dimensional structure of quartz
(Source: Dutch 2002).

Photo 2.1: Crystal structure of quartz
(Source: Lavinsky 2008)

Information provided by Champion & Mitragotri (2006) suggests that the shape of a particle in the lung plays an important role for the macrophages to effectively engulf and remove the particle. Figure 2.14 demonstrates that the particle shape and angle at which the macrophage approaches the particle is one determining step in phagocytosis. The more elongated the particle, the more difficult it is for a macrophage to engulf the particle (leading to frustrated phagocytosis) and longer the macrophage is exposed to reactive oxidative species from the cleaved crystal surface can be seen in row B of Figure 2.14.

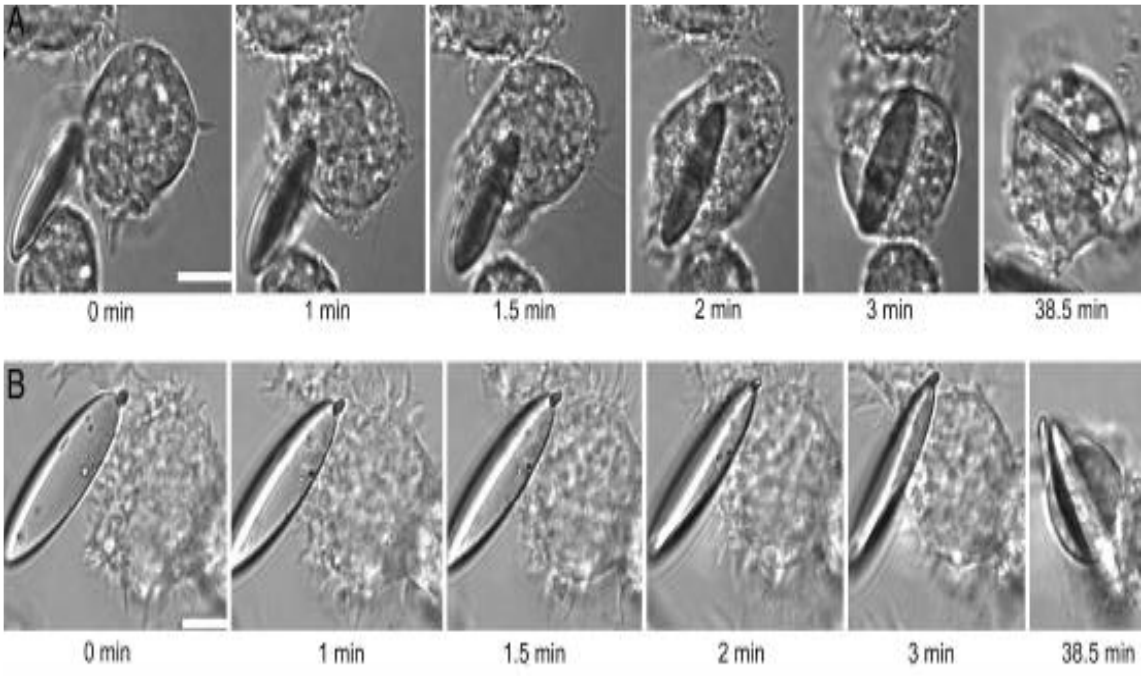


Figure 2.14: Time-elapsed video showing macrophages interacting with synthetic particles (Champion & Mitragotri, 2006, p. 4931).

Particle shape affects uptake and engulfment by macrophages, as the point of initial contact is important. The angle between the particle and membrane determines how the particle will be engulfed. Hiroto & Terada (2012) provide an example of engulfment of an elliptical-disk shaped particle. The particle is internalized when the macrophage contacts the particle from the end spreading around the particle then engulfing it. When the macrophage comes in contact with the long particle from the side, the particle may not be engulfed. Hirato & Terada (2012) provide an example where particles such as bacteria from 2 – 3 μm will be engulfed. It is now known that the particle surface of freshly cut quartz has a highly reactive surface area that interacts with the lung causing inflammation. It is therefore considered that particle surface area is the main risk factor leading to disease (Duffin et al. 2002). For freshly cut crystalline silica, the larger the surface area, the greater exposure to reactive oxidizing

sites. These sites are cytotoxic to the lung membrane and macrophages that try to remove these foreign bodies.

Fanizza et al. (2006) found that short-term exposure for 2 hours of human lung epithelial cells to pure quartz with a median diameter of 1.6μm resulted in oxidative DNA damage to the cells. This means that short-term exposure is an important factor when evaluating exposure and health symptoms. What is less clear is how particle size of crystalline silica equates to EAD which takes into account both density and particle shape. It is not straight-forward how particle shape influences particle motion and how particles are entrained in breathing air which reaches lungs. What is known is that fibrous minerals behave differently to spherical particles, in how they are transported in the breathing passages and how they are deposited in the lungs. Recent research has shown fibrous mineral particles with morphology as elliptical rods, or helices, will behave differently than straight symmetrical particles (Roshchenko et al. 2015).

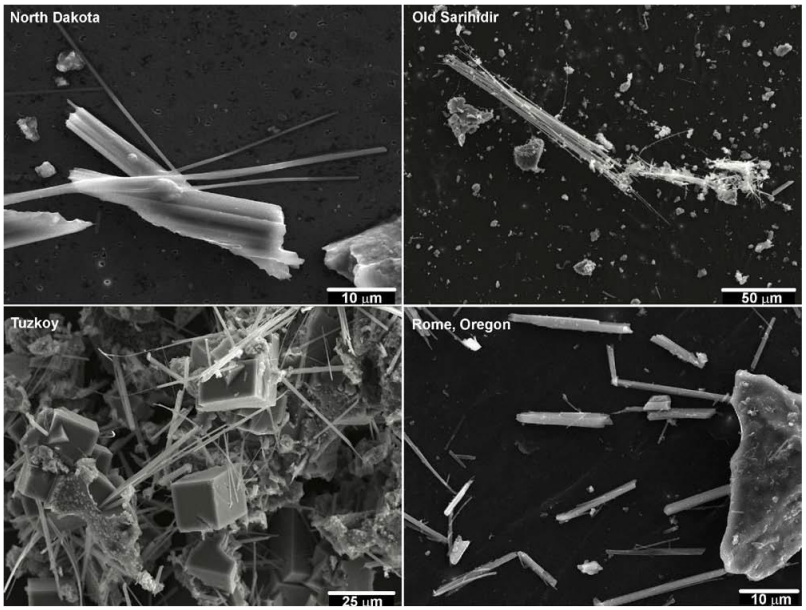
ISO (2012), have published an International Standard defining conventions for airborne particulate deposition in the human respiratory system. This standard still makes reference to 7708-1995, which normalizes aerodynamic diameter against the diameter of a sphere (ISO 1995). Many airborne particles will not be spheres nor will they behave as spheres. The International Standards Organisation (ISO) (2012) does provide a caveat in the following notes:

> 'The aerodynamic diameter is applicable to any particle, but is dependent on the density, shape and porosity of the particle' (ISO 2012, p. 1).
>
> Under conditions of interest in this International Standard, the aerodynamic diameter of a spherical particle is generally equal to $d\sqrt{(p/p_0)}$. (ISO 2012, p. 2)

No method has been provided by ISO (2012), to account for particle shape when calculating EAD from physical diameter.

Research carried out by Zhou et al, (2007 p.1071) found that it is easier for fibres to reach the upper respiratory tract and to reach the lower airways as compared to spherical particles. Zhou indicates that the fibre shaped particle will pass through the breathing airways more easily than spherical particles even if they have the same aerodynamic diameter. The orientation along with the flow is important as fibres may align with the air flow and then finally deposit in the alveolar region of the lungs Zhou et al., (2007). This is consistent with Sturm & Hoffman (2009) making mention that fibrous mineral orientation is considered to be approximately parallel to the airway wall in the peripheral airways. The peripheral or small airways are less than 2mm in diameter and extend from the bronchioles to the alveolar ducts. Timbrell cited in Liddel & Miller (1991) provides earlier research which demonstrates that interception as a deposition mechanism for lung deposition is highly significant for mineral fibres. Interception is the process where a particle does not deviate from the airstream and contacts the surface because of its physical size. The likelihood of interception depends on the closeness of the airway surface and the ratio of the particle size to air passages. The interception of a fibrous mineral, especially when symmetrical, will be equal to the particle physical diameter (Roshchenko et al. 2015). The literature does provide conventions to account for shape. Terms used for shape include shape factor Hassan & Lau (2009), form factor Hinds, (1999) and elongation factor (Milana et al. 2015). Elongation factor is defined as 1 - width / length and as the name indicates it is a measure of elongation and has values between 0 and 1. A symmetrical shape in all axes such as a circle will have an elongation factor of 0, whereas shapes with large aspect ratio will have an elongation factor closer to 1. Forms of silicate such as erionite (a zeolite), is shown to be chain like in a fibrous form (IARC 1987). Long-fibred erionite is found in many rock types and geological formations and from many locations around the world including Australia and Canada (Dogan 2011). Quantitative characterisation information of erionite is scarce in the literature. However, erionite is a confirmed human carcinogen (IARC group 1) and known to cause mesothelioma (Dogan 2011).

Refer to Photos 2.2 & 2.3 to observe particle shape (morphology) of erionite.



Photos 2.2: Representative morphology comparison of erionite from North Dakota, Old Sarihidir and Tuzkoy, Turkey, and Rome, Oregon (Source: United States Department of the Interior and Geological Survey, 2010, p. 4).

All samples shown in Photo 2.2 contained individual fibres, bundles of fibres, and radiating fibre bundles.

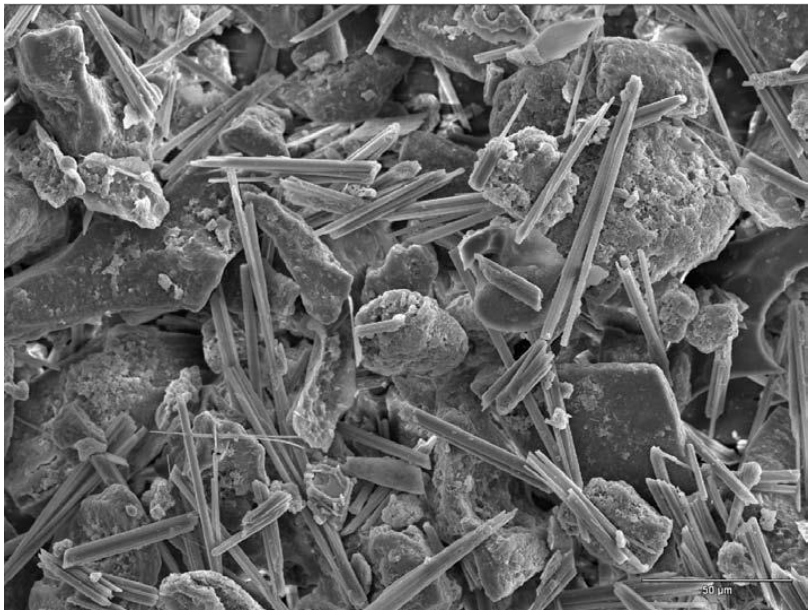


Photo 2.3: Morphology of erionite

(Source: United States Department of the Interior and Geological Survey 2010, p. 13)

Agglomeration will also play a role. The findings of Scheckman & McMurry (2011), demonstrated that agglomerated silica particles were observed to have significantly greater deposition in a cast of human lung airways, concluding that interception was responsible for this enhanced deposition.

2.8 Limitations using conventional size selective sampling techniques.

With an increase in the flow rate from 1.9 L/min to 2.2 L/min introduced in 2004, it was noted that there would be a lower number of larger particles collected under the new flow rate. The 2.2 L/min flow rate discards more particles from about 0.2 – 150 µm, and is density dependent, as described by Isabella, Glossop & Green (2004), and shown in Figure 2.15. It can also be seen from Figure 2.15 that the biggest difference for iron ore dust is at about 4 µm where a difference of 50% has been shown.

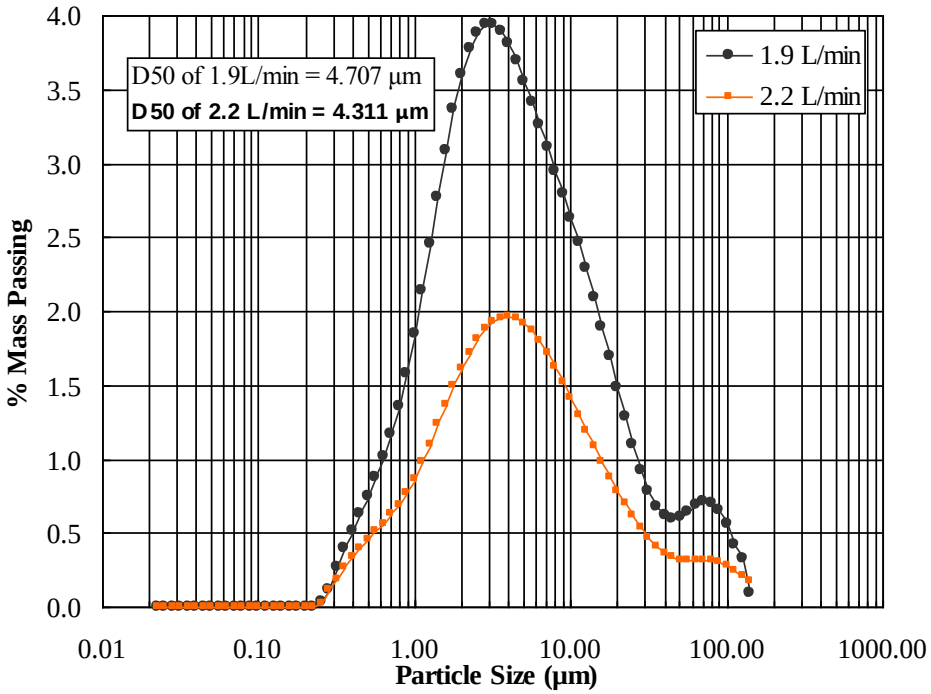


Figure 2.15. Light scattering particle size analysis of iron ore respirable dust collected from parallel paired samplers at flow rates of 1.9 and 2.2 L/min
(Source: Isabella, Glossop & Green 2004, p.2).

With the adoption of a different flow rate to measure respirable dust in AS 2985-2004 it was noted by Isabella, Glossop & Green. (2004), that there is a marked change in the mass of respirable particulate matter sampled. This may

be problematic especially when comparing respirable dust and RCS concentrations prior to and when the new flow rate was introduced in 2004. Pretorius (2011) demonstrated differences in accuracy and precision between cyclone samplers produced by different manufacturers. Differences in sampler manufacture included burrs in the inlet aperture, inlet aperture size and internal finishing, all of which can affect sampling efficiency. Pretorius (2011) also noted that the mineral dust type and composition can affect sampler performance. A non-uniform distribution of dust on the filter will also directly affect the analysis of dust samples using methods that include X-ray diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) (Pretorius 2011). Glossop (2004) challenged whether sampling the respirable dust fraction is relevant to the health risk. Glossop (2004) posited that more attention should be placed on assessing the risk for COPD and that inhalable dust fraction is a better indication of risk. Figure 2.16 identifies different sampling efficiency curves (Inhalable & Respirable) and medium diameter of airborne dust from an iron ore crushing and screening operation collected as total suspended particulate matter (TSP). Glossop (2004) emphasized that sampling respirable dust only will not account for all of the dust responsible for causing COPD and inhalable dust may be a better measure.

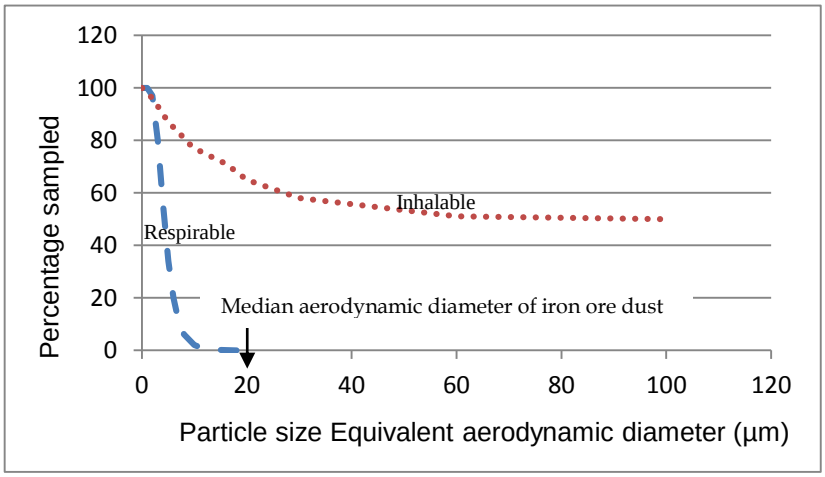


Figure 2.16 Median diameter of total suspended particulate for iron ore.
(Adapted from Glossop 2004, p.7).

When considering particle shape if the particles were spheres, as per stokes law and, Popendorf (2006) refers to the following formula:

$$dpa = dps\sqrt{Pp}$$

Where *dpa* = Aerodynamic diameter

dps = stokes diameter μm

Pp = particle density, gm/cm^2

Of course, in mines and quarries particles will not be perfect spheres. Another factor influencing particle size distribution is particle shape and reference is made to the following formula:

$$da = dg\sqrt{\frac{Pe}{\lambda Ps}}$$

Where da = Aerodynamic diameter

Ps = 1 g/cm^2

dg = particle geometric diameter

Pe = effective particle density in the same unit as Ps

(Hassan & Lau 2009, p.1252).

> 'The shape factor (λ) is defined as the ratio of the drag force of the particle to that of a sphere of an equivalent volume' (Hassan & Lau, p. 1252).

Elongated particles in this study have a length, diameter, and aspect ratio which will categorise them as respirable fibres. Fibres have a greater likelihood to be entrained in the air and penetrate into the lung as respirable fibres. This means that shape will play an important role.

ISO 13138 (2012, p.4) notes that:

> With coarse particles (aerodynamic equivalent diameter greater than about 0.5μm) such as those found in the mining environment, the conventional respirable fraction and aerosol particles deposited in the gas-exchange region correlate well with the mean.

No reference is provided in ISO 13138 (2012) to qualify this statement. Due to the heterogeneous nature of particle morphology in mining and considering that shape will greatly influence behavior which means that this statement is questionable.

2.9 Limitations in sensitivity of measurement.

Measuring silica at relatively low concentrations, and well below occupational exposure limits, leads to uncertainty in measurement.

Stacey (2007, p.4), noted that the

> 'limits of detection are optimistic of what can be achieved'.

Measurements at 0.025 mg/m^3, which is the Threshold Limit Value (TLV) used by the ACGIH, do not meet the maximum uncertainty of occupational hygiene measurements denoted in Figure 2.17.

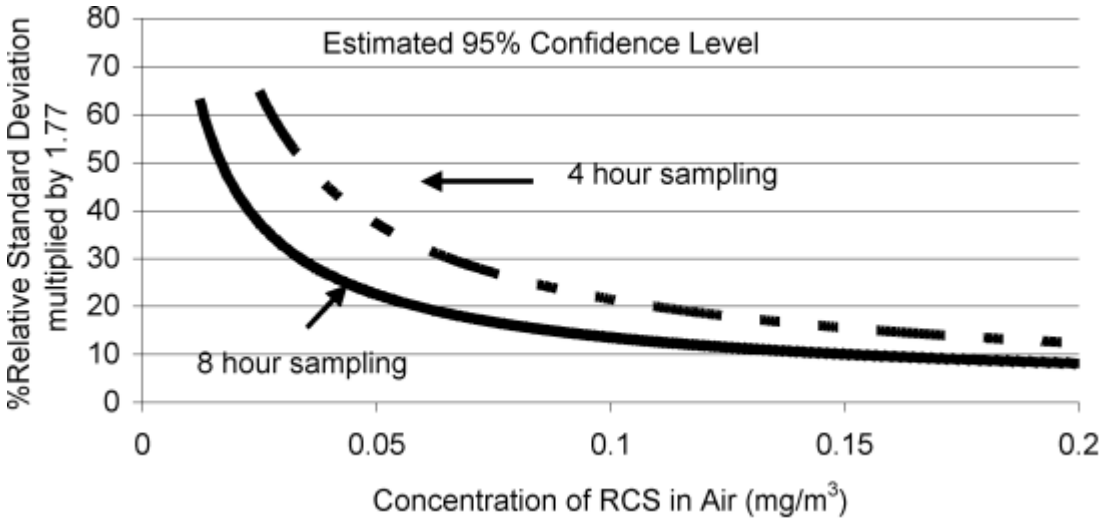


Figure 2.17: % relative standard deviation and the significant increase for small changes in the mass measures below 0.05 mg/m^3
(Source: Stacey 2007, p.3).

Stacey (2007) noted that many laboratories will not meet the European requirements, as per Table 2.8, especially if samples are taken for 4 hours at the ACGIH TLV of 0.025 mg/m^3 which means that it is not technically feasible to set a limit at this lower level.

Table 2.8 Workplace exposure: – General requirements for the performance of procedures for the measurement of chemical agents.
(Source: British Standards European Standards (BS EN) 482:2012, Workplace exposure. General requirements for the performance of procedures for the measurement of chemical agents, p.8)

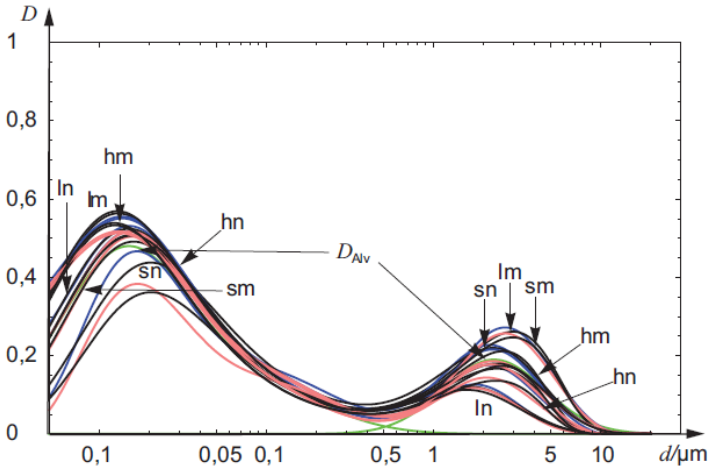
Reference period	Measuring range	Relative expanded uncertainty
Short-term (eg 15 min)	0.5 to 2 times limit values	≤ 50%
Long-term	0.1 to < 0.5 times limit value	≤ 50%
Long-term	0.5 to 2 times limit value	≤ 30%

Comparison of Table 2.8 with Figure 2.17 demonstrates that for a 4 hour sample, if the occupational exposure limit were 0.05 mg/m^3, the requirements of BS EN 482:2012 will not be achieved.

2.10 Advances in monitoring technology.

The original conventions based on experimental data from inhalation studies with human volunteers, were described as curves illustrating the penetration to the region of interest as a function of particle size. Since the 1960s the measure has been referred to as particle sized aerodynamic diameter in the size range extending from 0.5 to 100 μm (Walton et al. 1998). These conventions resulted in the development of samplers for collecting inhalable, thoracic and respirable mass fractions of airborne particles. According to ISO (2012), the conventions were deliberately set up conservatively in view of the large inter and intra person variability and it is acknowledged that the actual deposition of particles and true exposure differs from penetration to or within the alveolar region of the lung, especially with fine aerosols. ISO (2012) - notes that correlations between dust and exposure might be limited. These conventions have however, provided a mechanism by which simple samplers have been developed (ISO 2012). This suggests that the methodology for airborne particle sampling is not an exact science and limits studies carried out to correlate exposure with health effects. The more recent standard ISO (2012) now provides conventions for samplers intended to represent fractions of inhaled aerosol particles depositing in specific areas of the respiratory system where the particle size distribution is

extended down to below 0.1 µm (as shown in Figure 2.18), and where deposition is dominated by Brownian motion (or diffusion) (ISO 2012). This new standard challenges the adequacy of the conventional method, especially where the particle size distribution is dominated by particles < 0.5 µm, which are deposited in the alveolar region.



e) Alveolar region

Key

D	deposition	hm	heavy exercise, mouth breathing
d	spherical particle diameter	hn	heavy exercise, normal breathing
D_{Alv}	deposition in the alveolar region	lm	light exercise, mouth breathing
D_{BB}	deposition in tracheobronchial region 1	ln	light exercise, normal breathing
D_{bb}	deposition in tracheobronchial region 2	sm	sitting, mouth breathing
D_{ET_1}	deposition in extrathoracic region 1	sn	sitting, normal breathing
D_{ET_2}	deposition in extrathoracic region 2		

Figure 2.18. Deposition efficiencies into various regions as linear combinations of the proposed conventional functions at density ρ = 1g/cm^3 plotted in terms of geometric diameter d of a spherical particle; curves for males (blue) and females (red). Black represents conventions from ICRP publication 66 (1994) (Source: ISO 2012, p.14).

A recent development discussed in ISO (2012), is that the conventional design of a cyclone sampler is based on particle penetration and does not incorporate deposition. As the sampling and analysis using a cyclone is mass based and the median cut is 4.25 µm, sampling the larger particles may not provide an accurate estimate of risk where particles ≤3 µm are considered to be much more hazardous.

Volkwein, Maynard & Harper (2011, p.584) noted that:

> 'While penetration of particles to the airways system is a measure of exposure, it is not a good measure of dose for certain particle sizes'.

As mass is the conventional measure, then larger particles greater than 5 μm for instance, in the respirable dust sampling curve may overestimate the health risk, especially when there are fewer smaller particles less than say 3 μm. Conversely, when there are fewer larger particles say greater than 3 μm and a greater number of small particles less than 3 μm the risk to health will be under-estimated as it is a mass based measure. For smaller respirable dust particles the deposition fraction is important. This was demonstrated by Kuehl, et al. (2012) where rats were exposed to aerosols at 0.5, 1.0, 3.0 and 5.0 μm mass median aerodynamic diameters (MMAD).

Kuel, et al. (2012, p.27) noted that:

> The commonly used 10% deposition fraction for all aerosols between 1.0 and 5.0 μm does change with particle size. The deposition patterns of aerosols between 0.5 and 5.0 μm showed an increase in both overall and peripheral deposition as the particle size decreased.

Newer sampling techniques are required that consider the impact on health from deposition (Vincent 2005). The ICRP considered particle deposition as an important fact, as shown in Figure 2.21 and now considered in ISO, 2012 (Figure 2.19).

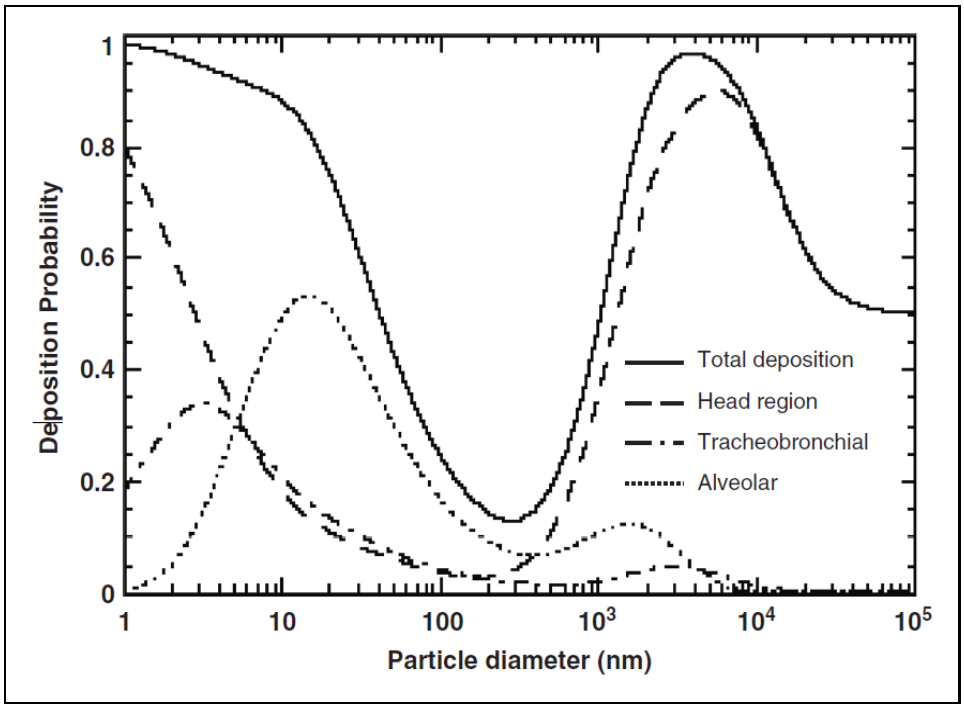


Figure 2.19: Predicted total and regional deposition of particles in the human respiratory tract related to particle size using International Commission for Radiological Protection (ICRP) 66 model (ICRP, 1994). The deposition fractions show the probability of particles being inhaled. The subject is considered to be a nose breather, performing standard work (Source: ICRP 1994).

As discussed previously, new sampling conventions must account for particle shape.

2.11 Health surveillance.

In the United Kingdom the HSE and the HSL have published a research report on health surveillance in silica exposed workers (HSL 2010). This report has been prepared to address the uncertainty about appropriate health surveillance for silica-exposed workers, and provides a comparison of health surveillance programs internationally, including the recommendations outlined in the DME Queensland (Australia) Mines Inspectorate Safety Bulletin – Management of dust containing crystalline silica (quartz) February 2010 (DME 2010).

ACOEM have recommended that both cross sectional and longitudinal spirometry needs to be carried out to provide a better estimate of risk (ACOEM

2006). More recently, SWA has published guidance material. The guide is intended for use by medical practitioners carrying out or supervising a health monitoring program for workers who may be exposed to crystalline silica (SWA 2013c).

2.11.1 ILO 2011 – Guidelines classification of radiographs of pneumoconiosis.

The International Labour Organisation (ILO) has released Guidelines for the use of the ILO International Classification of Radiographs of Pneumoconiosis (revised edition 2011). The Classification provides a means for describing and recording systematically the radiographic abnormalities in the chest provoked by the inhalation of dusts. It is used to describe radiographic abnormalities that occur in any type of pneumoconiosis and is designed for classifying only the appearances seen on postero-anterior chest radiographs (ILO 2011). The 2011 ILO guideline extends the applicability of the ILO international classification of pneumoconiosis beyond chest x-ray radiographs to digital radiographic images and designation of monitoring of technical quality.

The ILO (2011, p.19) note that

> It has long been recognized that the technique and equipment used for chest radiographic imaging of dust exposed workers affect the radiographic appearance of pneumoconiosis lesions, and this can influence the classification of pneumoconiosis.

Provision has therefore been made in the guideline ILO (2011, p.19) for defining technical grade 4 which means

> 'unacceptable for classification purposes'.

The system of classification is used for epidemiology and health surveillance of persons in dusty occupations for clinical diagnosis.

ILO (2011, p.1), notes that

> 'use of the scheme may lead to better international comparability of data concerning the pneumoconiosis'.

This may reduce the variability in x-ray interpretation.

Comparison of opacities, - meaning opaque areas, are compared with standard radiographs. Four categories are defined by standard radiographs. Profusion or quantity of opaque areas is classified into 12 sub-categories as shown in Table 2.9.

Table 2.9: ILO (2011, p.4) classification scheme for categorizing chest x-rays.

Increasing profusion of small opacities →												
Categories	**0**			**1**			**2**			**3**		
Subcategories	**0/–**	**0/0**	**0/1**	**1/0**	**1/1**	**1/2**	**2/1**	**2/2**	**2/3**	**3/2**	**3/3**	**3/+**

Affected zones of the lung and shape/size of the opacities and pleural abnormalities are also recorded. The pleural cavity is made up of the outer pleura attached to the chest wall and inner pleura which cover the lungs, blood vessels, bronchi and nerves. Localized pleural thickening is recorded if the width is greater than 3 mm (ILO 2011). The National Institute for Occupational Safety and Health (NIOSH 2012b) proposed to allow for digital chest imaging under the US Coal Workers Health Surveillance Program (CWHSP) and these new regulations were subsequently adopted.

The introduction of high-resolution computed tomography (HRCT) has also improved the diagnosis of occupational lung disease; however a comprehensive system for the classification and quantification of these lung abnormalities on HRCT is still not in common use.

However, according to Bhawna et al. (2013, p.2):

> 'the awareness about the radiological manifestations of occupational lung disease is still limited with uncertainty associated with the terminology and description of radiological manifestations'.

2.11.2 Spirometry

Spirometry is a measure of lung health. Spirometry when done properly is a reproducible and objective measurement of airflow limitation (Global Initiative for Chronic Obstructive Lung Disease Inc. (GOLD) 2015). Spirometry is the measurement of respired air and is a test of lung performance. A spirometer is used to measure how much air is exhaled, and in some situations inhaled, and the time it takes to do so. To carry out a lung function measurement the test subject has to ensure that they give maximum effort when breathing into the spirometer. Coaching is required to instruct the subject how to do this effectively and 'it is important that the operator is properly trained' (Johns & Pierce 2007, p.26). The test must be repeated a number of times, normally three, until these repeat tests within tolerance (Johns & Pierce 2007). A spirogram (graph) is produced from this test and the curve is used to evaluate test performance and identify patient related problems. Different measurements are produced from the spirogram. A sensitive measure of performance is forced expired volume in the first second (FEV1), which determines how quickly full lungs can be emptied (Johns & Pierce 2007). FEV1 % of predicted: compares patients FEV1 to a healthy person, of the same age, height and gender. Different reference populations are used to select normal readings from healthy individuals. NIOSH recommends selecting reference values based on the third National Health and Nutrition examination survey (NHANES III). These

reference values are based on a random sample of the United States population (ACOEM 2006). According to Pierce (2005), measurement of lung function is fundamental to the assessment of respiratory health and should be routinely applied in the primary care setting in patients with known or suspected respiratory disease. It has been reported that the widespread use of spirometry will improve respiratory health and reduce the burden of respiratory illness in the community.

Pierce (2005, p.539) stated that:

> 'spirometric measurement is critical to the diagnosis and management of asthma, COPD and restrictive lung disease'.

Spirometers can be categorised as either volume displacement or flow spirometers depending on whether they primarily measure volume or flow. Flow spirometers are most commonly used due to their portability and lower cost. Volume-displacement spirometers are most familiar to clinicians and are widely used in respiratory laboratories, general practice clinics, and epidemiological surveys (Pierce 2007). Timed measurements are made of the lung volume and capacity during forced expiration to determine how quickly the lungs can be emptied and filled. The FEV1 % of predicted is generally used to grade severity in patients with obstructive, restrictive and mixed pulmonary defects. Pellegrino et al. (2005) provides data which can be used to rate the level of severity (Table 2.10).

Table 2.10. Severity of any spirometric abnormality based on the forced expiratory volume in one second (FEV1)
(Source: Pellegrino et al. 2005. p.957).

Degree of severity	FEV1 % of predicted
Mild	> 70#
Moderate	60 - 69
Moderately severe	50 - 59
Severe	35 - 49
Very severe	< 35

Although an arbitrary general lower limit of normal (LLN) is used at 80% of the predicted value, ACOEM recommended that this should not be used in an occupational health setting (Townsend et al. 2011). Using FEV1 at 80% of predicted as a lower limit of normal is considered acceptable for children, but can lead to errors when interpreting lung function in adults (Pellegrino 2005). On the other hand, the HSE (2015) use of FEV1 or FVC <'80% of predicted, as an abnormal result, will trigger referral to a health professional. The HSE (2016) have released supplementary health surveillance guidance for health professionals. The HSE (2016) guidance includes health surveillance (health professional) reference criteria for workers exposed to RCS a respiratory questionnaire pro-forma and criteria forabnormal lung function results which includes the following:

- a reduction in the FEV1/FVC ratio to less than 0.7 (70%); or
- a reduction in the percentage predicted FEV1 and/or percentage predicted FVC to less than 80% of the predicted value;

accelerated annual decline in FEV1, measured over time as follows:

- FEV1 fall over one year of 500 mL or more; or
- FEV1 fall over 5 years of 500 mL (an average of 100 mL per each year) (HSE 2016, p.3).

To standardise spirometry and acceptability of test results, Miller et al. (2005) has provided criteria which applies to each individual test result. The accuracy of the spirometer has to be checked using a 3-litre calibration syringe and when 3 litres are passed through the spirometer a volume to within ± 3.5% is required (Pierce, 2007; Miller et al. 2005). When carrying out spirometry the protocol for testing must be strictly adhered to with 3-repeat measurements taken for each individual. Where the repeatability criteria are not met then repeat measurements are required until the two largest measurements are within tolerance (0.15 L). The largest value is typically reported. Where the repeatability criteria are not met,

'FEV1 may still be valid if cough or premature termination of the blow occurs after the first second' (Pierce 2007, p.30).

The Thoracic Society and European Respiratory Society have set minimum requirements for all spirometers and these have been summarised by Pierce (2007).

SPIROLA, a NIOSH based software, has been specifically developed to assess changes in lung function with time and could easily be adopted for use within a health surveillance program. The following URL is provided for SPIROLA: http://www.cdc.gov/niosh/topics/spirometry/spirola-software.html. (NIOSH 2014). According to NIOSH improvements in this version include: addition of Asian-American race/ethnicity reference equations, functions to help users identify duplicate or incorrect data, and bug fixes improving the software speed. NIOSH is also developing a web-based version of SPIROLA which NIOSH suggests will improve usability and flexibility of the application (NIOSH 2014).

2.11.3 Respiratory questionnaire

The first standardized respiratory questionnaire as proposed by the British Medical Research Council (BMRC) was first published in 1960 (MRC 1960) to investigate the epidemiology of chronic bronchitis and chronic airway obstruction. From the 1960s to 1970s, the main focus of the research was on chronic bronchitis, emphysema, and chronic airway obstruction. Questions mainly related to respiratory symptoms such as cough, phlegm, and dyspnoea (breathlessness), and investigated risk factors were smoking and occupational exposures (Bellia et al. 2003). The BMRC (1986) respiratory questionnaire has been validated by a number of organisations. The NSW Coal Services in 2011 recommended the BMR questionnaire as part of pre-placement and periodic medical assessments.

The Institute for Risk Assessment Sciences (IRAS) in the Netherlands has recently developed a simple diagnostic model to estimate the probability of individual workers having pneumoconiosis using both a questionnaire and spirometry results, based on a large cross-sectional study of Dutch stone and construction workers with potentially high RCS exposure (Suartha et al. 2007).

The HSE (2015) have recently published a respirable crystalline silica health surveillance baseline record, which incorporates work history, the use of respiratory protective equipment and respiratory questionnaire.

2.11.4 Other health surveillance including biological monitoring.

Biological monitoring of health effects is becoming more established and the 9th International Symposium in Biological Monitoring in Occupational and Environmental Health, Manchester, UK (September 2013) provided an update on a longitudinal study of workers exposed to silica being conducted by the UK Health and Safety Laboratory. Individual exposure estimates for those workers who have volunteered for the study are being calculated from atmospheric measurements and job histories. Health outcome measures currently in use include respiratory and general health questionnaires, lung function tests and chest x-rays, as well as a panel of effect biomarkers. These biomarkers include the lung markers, Clara cell protein (CC16), lung surfactant proteins (A&D) and a panel of renal markers that includes kidney injury molecule-1 (KIM-1), neutrophil gelatinase -associated lipocalin (NGAL) and cystatin C. Biomarkers reflecting inflammatory response and protein oxidation/nitrosylation are also being measured related to silica exposure, particularly lung and renal damage, measured in blood and urine (HSL 2013). A major role of biological monitoring effect biomarkers is to identify early signs of upcoming disease and put forward strategies to prevent the development of irreversible outcomes such as cancer. Geno toxicity testing has been carried out on persons exposed to dust containing crystalline silica at workplaces in Turkey (Demircigil et al. 2010). Although the study in Turkey has demonstrated significant increased micronucleus frequencies for workers compared to a control group (Demircigil

et al. 2010), the study has not been able to demonstrate a dose response relationship.

2.12 Research needs.

This review has revealed a number of gaps in the research literature. Firstly, no cross-sectional study could be found where similar exposure groups (SEGs) were pooled across a number of sites including quarry and dimension stone mines. No attempts were found where RCS and loss of lung function were measured at the same time, and correlated as a group to make comparisons between SEGs. As previously discussed the ACOEM recommended that both cross sectional and longitudinal spirometry needs to be carried out to provide a better estimate of risk (ACOEM 2006). Most literature assesses spirometry longitudinally with no direct measure of RCS exposure at the time of lung function testing.

In addition Pierce (2005, p.539) noted that:

> 'spirometric measurement is critical to the diagnosis and management of asthma, COPD and restrictive lung disease'.

It is well known that COPD can be caused by exposure to RCS and the presence of both obstructive and restrictive lung disease is a significant predictor of earlier death (Mannino et al. 2003). From this review, assessing exposure to RCS in parallel with spirometry and a respiratory questionnaire will advance the research in prediction of potential health impacts on workers in the mining industry.

Analysis of particle size distribution and particle shape of dust in air being inhaled by mine workers will also assist in the prediction of the risk to health.

If a correlation between RCS and loss of lung function can be demonstrated at the current SWA-ES, then these findings will challenge the adequacy of that exposure standard.

Apart from work presented by Isabella, Glossop & Green (2004), which compared the sampling efficiency of the respirable cyclone sampler using different flow-rates to sample iron ore dust, particle size distribution analysis studies for airborne dust in quarries and dimension stone mines have not been found in this literature review. As previously discussed, according to Kerr, Vincent & Ramachandran (2001) the assessment of the true health-related dose received by a worker, possibly leading to ill-health from inhalation, requires full characterization of the aerosol as a function of particle size distribution and chemical species. Vincent (2005) reported that some occupational health experts have expressed concerns about fine particles and ultra-fine particulate aerosols. This is an important point as it is generally assumed that silicosis is caused by the fraction of silica that reaches the alveoli (Office of the Environmental Health Hazard Assessment 2005; King et al. 1953). Particle shape must also be considered in the health risk assessment.

The research questions to be addressed in this thesis are:

1. Does exposure to RCS dust at the current SWA-ES have an adverse impact on lung function?
2. Does the installation of air-filtration RESPA© technology, on the cabins of excavators used in dimension stone mines result in lower concentrations of RCS in cabin air?
3. Using electron microscopy (EM), what are RCS particle shapes and sizes found of in Queensland quarries.

Chapter 3.0 Methods

3.1 Selection of study sites

The selection of study sites (seen in Table 3.1) for this research was based on geographic location within Queensland as well as silica content of extracted rock. The estimate of silica content was determined through discussion with the Queensland Department of Mines Geologist, who graded the operations as either low, medium or high. The criterion was to cover the southern, central and northern operations of Queensland and where possible to include sites that had different processes and different rock types. The sampling was also scheduled to coincide with other priority work at each mine site to maximise the number of operations that could be tested.

Table 3.1 Research study sites, showing regions within Queensland, and silica content of rock based on geology at each site selected.

Study site code	Operation	Region	Silica content
A	Dimension sandstone mine	South	High
R	Dimension sandstone mine	South	High
P	Sand, soil and gravel	North	High
FV	Aggregate, rock and sand (andesite).	Central	Medium
Y	Hornfels and basalt rock	Central	Low
H	Aggregate	Central	Unknown
Fo	Sand, soil and gravel	Central	Medium
C	Sand processing, screening plant	South	High
N	Sand processing, screening plant	South	High

Although the selected sites were not considered representative of all mines and quarry sites across Queensland, they do have a range of crystalline silica in the rock type qualitatively ranging from low to high (Table 3.1). This selection of various sites with differences in rock type allows a range of exposures to be explored. In addition, comparing exposure with lung function will establish whether there is in fact a dose response curve for exposures at and below the SWA-ES of 0.1 mg/m^3 (SWA 2013).

3.2 Ensuring confidentiality

Each study site was coded with the first letter of the site name. Workers who participated in personal exposure monitoring and spirometry were given a number next to the site code. For example the stonemason at site A, was given a de-identified descriptor of A2. All monitoring forms, health surveillance records, including lung function test reports and respiratory questionnaires were given the same descriptor. Each worker was also assigned to a job type (or similar exposure group - SEG).

3.3 Correspondence with Site Senior Executives (SSE)

Prior to monitoring at each site, a letter introducing the researcher, and the type of research to be conducted (Appendix B) was provided to the SSE, a participant SSE consent form (Appendix C), and a participant worker consent form (Appendix D) along with an information sheet (Appendix E), was given to and received from the SSE and study participant workers.

3.4 Air monitoring

3.4.1 Full shift personal exposure monitoring

To measure personal exposure to RCS, samples were collected according to AS2985-2009 using a cyclone sampling head attached to a sampling pump at a flow rate of 2.2 (± 5%) L/min using SKC AirCheck 2000 Model 210-2002 sampling pumps. The pumps were calibrated using a TSI 4100® series (Serial No.4146 0629 001) mass flow meter. The TSI® secondary flow-meter was calibrated against a primary soap film flow-meter as per appendix B of AS2985-2009. A correction factor was calculated and all sampling volumes were adjusted to align with the primary standard. Wherever possible full shift monitoring was undertaken where cyclone samplers were placed on participants at the start and end of their shift. The samples were collected on SKC GLA-5000® PVC 25mm 5 μm pore size filters.

Only one sampler was placed each worker for full shift monitoring. The intention was to sample 3 different workers for each SEG and where possible aim for 6 samples per SEG and 2 samples per worker. This would allow a minimum sample number for statistical analysis (Grantham & Firth, 2014). When measuring occupational exposures, according to Ignacio & Bullock (2006, p.89):

> 'minimum measurements are needed to estimate the parameters with acceptably small uncertainty'.
>
> 'At least 6 random measurements should be taken for each SEG monitored, unless measured exposures are much less than the occupational exposure limit (OEL) (<10%) or greater than the OEL, in which case it may be possible to reach a decision with fewer measurements' (Ignacio & Bullock 2006, p.90).

3.4.2 Fixed position monitoring

Cyclone samplers were positioned inside the cabin of an excavator. The excavator had a circular saw attachment cutting through sandstone. These samplers were therefore positioned inside these cabins to evaluate personal exposures to operators inside these cabins and to determine effectiveness of the cabin filtration. Fixed position monitoring was carried out before and after installation of newer RESPA® technology which cleans air entering the cabin, to measure the effectiveness of this technology.

3.4.3 Continuous monitoring and particle size analysis

Testing the potential impact of an air cleaning device (RESPA®) on the air quality inside the cabins of mining machinery was undertaken. An RESPA® HVAC PreCleaner+Filter+Pressuriser unit was retrofitted into an excavator (LSM Technologies Ptd Ltd, Brisbane, Queensland, Australia). Retrofitting included all associated plumbing and commissioning. The RESPA® unit supplied and fitted by LSM Technologies Pty Ltd provided positive pressure

HEPA filtered air to the existing air conditioning system. This equipment is suitable and approved for both fixed and mobile mining plant. Sampling for a range of particle sizes was carried out using a DRX TSI® dust analyzer (Model 8533, Serial No. 8533084003) which can sample for PM_1, $PM_{2.5}$, PM_{10} and respirable concentrations simultaneously. Respirable dust was also measured in the same excavator cabin using AM510 TSI® dust analysers (Serial Nos 10809003, 10809004 & 10809005). Both these instruments allow for real time sequential measurements throughout the day in terms of changes in dust concentrations.

3.4.4 Laboratory analysis for RCS

The analysis of samples for RCS was undertaken at the Safety in Mines Testing and Research Station (Simtars) laboratories in Queensland in accordance with the National Health and Medical Research Council (NH&MRC) (1994) guidelines – Methods for Measurement of Quartz in Respirable Dust by Infrared Spectroscopy.

3.4.5 Laboratory analysis using electron microscopy

Filters were selected for particle characterisation by scanning electron microscopy (SEM) and elemental analysis by energy dispersive spectroscopy (EDS). The filter samples which were initially analysed for RCS were sent to Microanalysis Australia located at Victoria Park, Western Australia, for a more detailed analysis of particle size and shape. A representative sub-sample, of approximately 6 mm by 6 mm, was cut from each filter membrane close to the centre. The sub-sample was placed on top of a double sided carbon tab before being carbon coated. The sample was analysed using a JEOL 5800LV SEM fitted with an Oxford INCA EDS. EDS is a semi-quantitative technique on prepared, optically flat samples which has a spatial resolution of ~5 μm. This means that spectra from particles less than ~5 μm may contain elemental concentrations biased by their surroundings. All images were acquired using measuring backscatter electrons. Image brightness is proportional to average atomic

number: the brighter the pixel, the higher the atomic number of the element. Images were taken of each sub-sample and the particles present analysed for their elemental composition and size. When the particles were not spherical, the largest dimension was determined.

3.4.6 Adjustment of exposure standards for extended shifts

Extended shifts beyond a standard 8-hr work day are commonly worked in mines and quarries. As SWA-ES apply to an 8-hr shift, if shifts are longer an adjustment must be made to this Exposure Standard. The Brief & Scala method is the most conservative model for adjusting occupational exposure limits downward as recommended by SWA (AIOH 2013).

Therefore, exposure standards for respirable dust and respirable silica have been adjusted applying the Brief and Scala model using the average weekly hours adjustment equation as recommended by Simtars (nd):

$$RF = \frac{40}{h} * \frac{168 - h}{128}$$

Where: h = average hours worked per week over full roster cycle.
RF = reduction factor

This formula is consistent with SWA (2012, p.29) for the weekly adjustment formula.

3.5 Spirometry

Lung function testing was undertaken using an Easyone® spirometer (Model 2001, Serial No 66033/2008). The method used followed the method described by Brusaco, Crapo and Viegi cited by Miller et al. (2005). The spirometer prediction parameter was set on National Health and Nutrition examination survey (NHANES III) (Hardie et al. 2002). The system interpretation was Global

Initiative for Chronic Obstructive Lung Disease (GOLD) /Hardie (Hardie et al. 2002), and the best value result was used for interpretation as recommended by Queensland Health. The ndd EasyGuide Operator's Manual was followed for the Gold/Hardie Interpretation ndd Medical Technologies, (2010, p.24). NIOSH notes that the reference values are based on NHANES III; which are based on a random sample of the United States population (ACOEM 2006) where spirometry data were collected from 20,627 survey participants (Hankinson et al. 1999). Training was provided to the research team in spirometry by the Queensland Health, Department of Respiratory Medicine Laboratory. This training was carried out as per section 4 of the Queensland Health (2012) Spirometry Training and in accordance with the Australian and New Zealand Society of Respiratory Science and the Thoracic Society of Australia and New Zealand (Swanney et al. 2012). All spirometry was carried out by the research team prior to workers commencing their shift.

The indices measured and recorded included:

- FEV_1 (Forced Expired Volume in 1 Second) measured in Litres, which is the volume of air exhaled in the 1st second.
- FVC (Forced Vital Capacity) measured in Litres, which is the total amount of air exhaled.
- FEV_1/FVC is the ratio of the two measures (%) and provides an indication of airflow obstruction.

3.6 Respiratory questionnaire

The respiratory Questionnaire used was based on the MRC (UK) Respiratory Questionnaire 1986. Additional questions have been added to cover clinical aspects of bronchial hyper responsiveness validated by the Department of Occupational and Environmental Medicine, National Lung Institute (Venables, Farrer & Sharp 1993). The British Occupational Health Research Foundation (BOHRF) (2004) concluded that in the clinical setting questionnaires that

identify symptoms of wheeze and/or shortness of breath which improve on days away from work or on holidays have a high sensitivity, but relatively low specificity for occupational asthma.

3.7 Interpretation of results and statistical analysis

Most occupational hygiene statistical analysis was carried out using the American Industrial Hygiene Association (AIHA) statistical package known as IHSTAT®. This is a Microsoft Excel™ based package which provides a graphical visualization of exposure distributions. IHSTAT® also calculates a number of occupational hygiene parameters such as the estimated average for log-normally distributed exposure data known as the minimum variance unbiased estimate (MVUE) and upper confidence limit (lands exact) of the exposure data. This package also assesses line of best fit for the exposure data to determine whether exposure is log-normal, normal or non-parametric (Firth & Grantham 2014). When evaluating exposures, a major consideration is the adjustment of the SWA-ES which have been set for 8-hr shifts, and adjusting these limits for extended shifts. This has been discussed and a formula for weekly adjustment to the SWA-ES has been provided in section 3.4.6. On average workers across all operations worked about 9 hours per shift and 45 hours per week. Applying the SWA-ES weekly reduction factor (RF), determined from the formula in section 3.4.6, this reduces the SWA-ES from 0.1 mg/m^3 (TWA) to 0.09 mg/m3 (TWA). Results from personal exposure monitoring for RCS and respirable dust were pooled for each similar exposure group (SEG). The estimated average for each SEG was calculated using the MVUE and lands exact upper confidence limit (UCL). The MVUE is the estimated average of a log-normally distributed data set. A test was carried out to determine whether distributions were log-normal or normal. The MVUE and UCL for each group were compared to the SWA-ES for RCS. To obtain a clearer picture of the potential risk of RCS to health, further analysis was undertaken to compare the MVUE with the loss of lung function measured as FEV1 % of predicted and FEV1/FVC % of predicted. The data analysis add-in feature of Excel® was used to evaluate the correlation for both linear and curvilinear curves to determine the curve of best fit. Excel®

allows analysis of the Kolmogorov goodness of fit tests (Miller & Miller 1984) and also calculation of probability of correlation of log-transformed values and determines whether the correlation coefficient calculated was significant (Miller & Miller 1984). Analysis of variance (ANOVA) was carried out to verify if there was a significant difference between exposures of similar exposure groups (SEGs) to RCS. Natural log (LN) transformed mean confidence intervals were calculated and compared using Minitab® and the data analysis add-in feature of Excel®. To determine what particle sizes were predominant in the respirable dust samples the distribution of particle sizes was calculated using the results from particle size analysis. Distributions of particle sizes were also profiled using IHSTAT® and EXCEL®.

3.8 Information provided back to each study site

Each study site was provided with follow-up through mine record entries (MRE). Where exposures exceeded SWA-ES, sub-standard conditions of practice were included in each MRE with actions being tracked to closure.

3.9 Information provided back to industry

Feedback from the research was presented at the Quarrying Safety and Health seminars at both Bardon and Townsville in 2010. The full report is also publically available through the Queensland Government, DME (2009b), RESPA® Trial 2009. Occupational hygiene monitoring for airborne particulate matter and respirable crystalline silica was carried out inside an excavator cabin, cutting sandstone, before and after fitting a pre-cleaner, filter and pressurisation unit.

3.10 Presentation of results

The results of the current studies are presented in Chapters 4, 5 and 6. Chapter 4 provides the results and discussion on the RESPA® study. Data were also collected on cabin pressurization and filtration technology for frequently used large mining machinery and these are presented and discussed in Chapter 4.

Chapter 5 provides tabulated and graphical personal exposure results of analysis, lung function testing, particle size analysis and statistical analysis. Chapter 6 provides an interpretation of analysis of select RCS filter samples by electron microscopy. Electron microscopy was carried out to better understand cyclone sampler collection and risk to lung health from RCS inhalation. Important properties of respirable crystalline silica samples, such as particle shape and size have been explored.

Chapter 4 RESPA® Study

4.0 Introduction

A review of the literature revealed that freshly cut crystalline silica has a higher degree of potency when compared to aged crystalline silica (HSE 2002). In quarries and mining sites there are many work stations where workers are in contact with freshly cut crystalline silica. This may mean that if a worker breaths a relatively high concentration of RCS for a short duration of time this may be more hazardous than breathing in a lower concentration over a longer period of time. Both types of exposure are undesirable and may affect long-term health, as has been shown in a number of international studies and reports (NIOSH 2002; Buchanan, Miller & Souter 2003; IARC2012a). Workers undertaking certain job types such as excavator saw operators in dimension stone forming mines are at increased risk of elevated exposures to RCS. In a survey conducted by the United Kingdom HSE, HSL they found that in many locations, engineering control equipment installed was of limited effectiveness, due either to the selection of unsuitable equipment, inadequate design or installation faults (HSL 2009). Where controls are installed, such as mobile machinery air filtration systems, it is important that the effectiveness of these controls be evaluated. To assess the potential worker exposure to undesirable RCS dust it was decided to test air quality in a common work environment in the Queensland mining industry. To target which work area of a mining site to conduct the work, a questionnaire was circulated to 420 quarries, dimension stone mines and sand processing plants throughout Queensland. Based on data collected from the survey, the air-conditioned cabin of a mining excavator was selected for investigation. This chapter describes an experiment which measures dust in the immediate environment of an excavator operator, and also the level of dust inhalation in an 8 hour shift. Modifications to the air filtration system were also trialled, to see if air quality in the work environment could be improved.

4.1 Main dust controls from self-assessment

Self-assessment questionnaires sent to SSE at selected quarrying operations revealed that air-conditioned cabins are often used (90%) in mining machinery to control exposure to airborne dust (Figure 4.1). Other exposure reduction actions included wearing of personal protective equipment, road watering and water sprays.

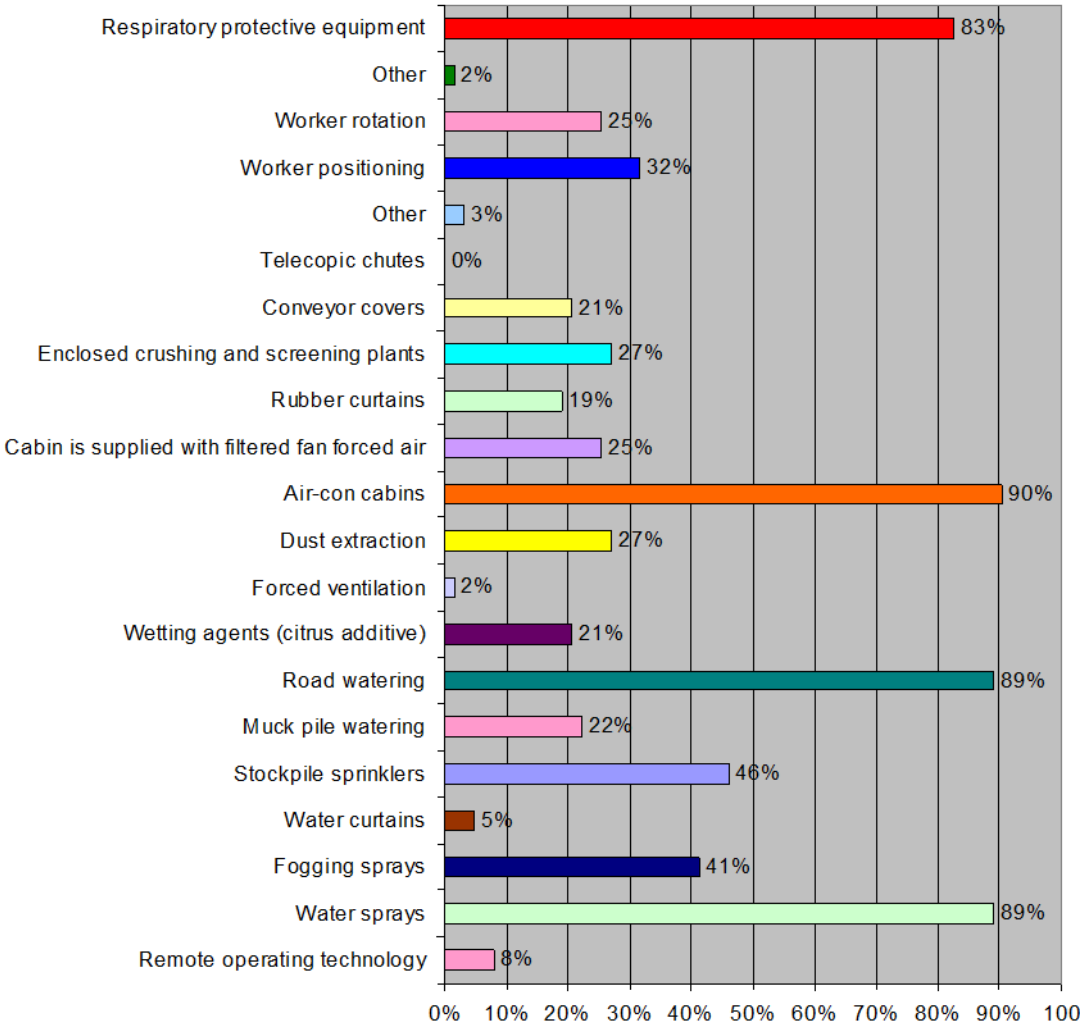


Figure 4.1 Controls used in quarries to reduce exposure to dust containing respirable crystalline silica

Although air conditioned cabins in mining machinery and at work stations such as rock crushing plants were the most widely used protection against exposure to airborne dust, only a small percentage of these cabins (25%) supplied filtered air under positive pressure. In order to be able to filter out the sub-micron particles, filtration systems need to be of higher efficiency grade and the cabin should be operating under positive pressure to prevent the ingress of dust. An excavator fitted with a saw v-cutting through sandstone is shown in Photo 4.1. Airborne dust is clearly visible around the saw blade, and in the air near the operator cabin. The Photo further reaffirms the need for protection of cabin based workers from RCS.

Photo 4.1: Excavator and circular saw blade cutting through sandstone.

Although Organiscak & Cecala, (2008) and DME (2009b) report that a primary means of dust control on mechanized surface mining equipment is the use of enclosed operator cabins with an air filtration system, it is also likely that fine particulate matter will ingress the cabin space unless the cabin air-conditioning system is under positive pressure.

4.2 Technology to prevent dust entering cabins

Newer technology to prevent the ingress of dust into mine machinery cabins is the RESPA® pre-cleaner, filter, pressurization (PFP) technology. These RESPA® PFP units can be mounted vertically or horizontally on stationary or mobile equipment and supply existing, heating, ventilation and air-conditioning (HVAC) systems with clean filtered fresh air, resulting in positive pressure within an operator cabin (Photos 4.2 and 4.3).

Photo 4.2 RESPA® PFP (new air-cleaning technology) unit mounted behind the cabin of an Excavator.

Photo 4.3 Close-up of the RESPA® PFP unit mounted behind the cabin of an Excavator

4.3 RESPA® study trials

Trials to monitor cabin dust levels in the cabin of the excavator shown in Photo 4.1, and personal exposure monitoring were conducted prior to and post installation of a:

RESPA® SD unit which pre-cleans and filters externally supplied air and,

an RESPA® SDX which filters re-circulated air.

The RESPA® HVAC Precleaner + Filtration + Pressuriser units were supplied and installed by LSM Technologies Pty Ltd. The Site Senior Executive (SSE) provided the excavator for retrofitting and LSM Technologies fitted the RESPA® system including associated plumbing and commissioning. RESPA® PFP units supplied in Australia by LSM Technologies Pty Ltd combine the technology of a Pre-cleaner, Filtration and Pressurisation units that provide positive pressure HEPA filtered air to the existing air conditioning systems of fixed and mobile mining plant.

Photo 4.4 Close-up of the RESPA® PFP and second unit mounted behind the cabin of an Excavator.

Monitoring undertaken inside the excavator (with saw attachment) cabin demonstrated that there is reduced exposure to both airborne particulate matter and RCS after installing an RESPA® pre-cleaner, filter and pressurisation (PFP) unit (Figures 4.2, 4.3 and 4.4). Sampling for a range of particle sizes was carried out using a TSI® DRX dust analyzer (Model 8533, Serial No. 8533084003) which can sample for PM1, PM2.5, PM10 and respirable concentrations simultaneously. Respirable dust was also measured in the same excavator cabin using an AM510 TSI® dust analyser (Serial Nos 10809003, 10809004 & 10809005). Both the DRX TSI® and AM510 TSI® dust analysers allow for real time sequential measurements throughout the day in terms of changes in dust concentrations. Air monitoring carried out within the cabin of 330CAT® and 350LCH Hitachi® excavators (with saw attachment) revealed that the standard fitted cabin air-conditioning / filtration system did not provide sufficient protection against airborne particulate matter and respirable crystalline silica

(RCS). These findings were reproduced and replicated using different monitoring techniques. The reduction was consistent over a range of particle sizes down to PM_1 as shown in Figures 4.2 and 4.3.

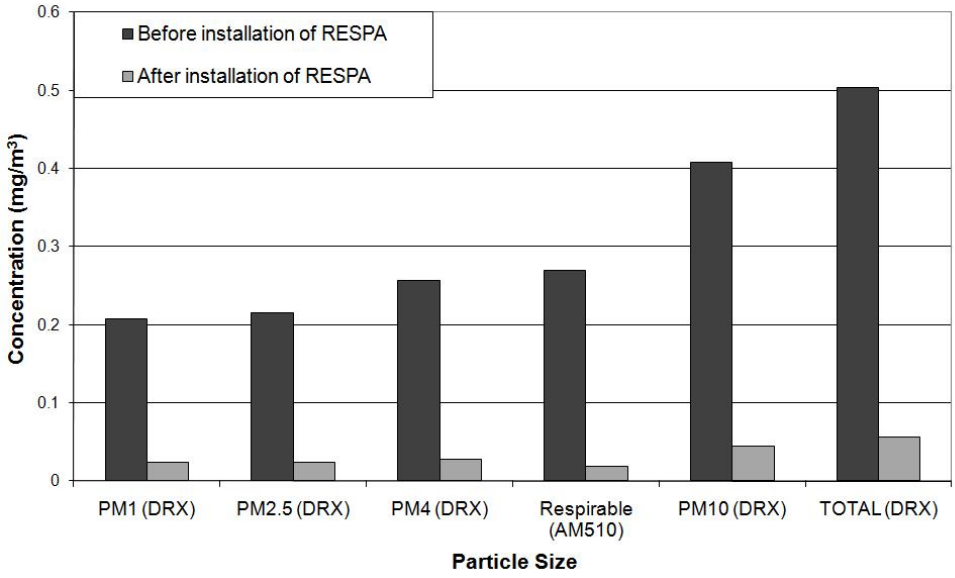


Figure 4.2 Fixed-position monitoring during trenching, demonstrates that there is an overall reduction in particulate matter and respirable crystalline silica once the RESPA SD® unit had been installed.

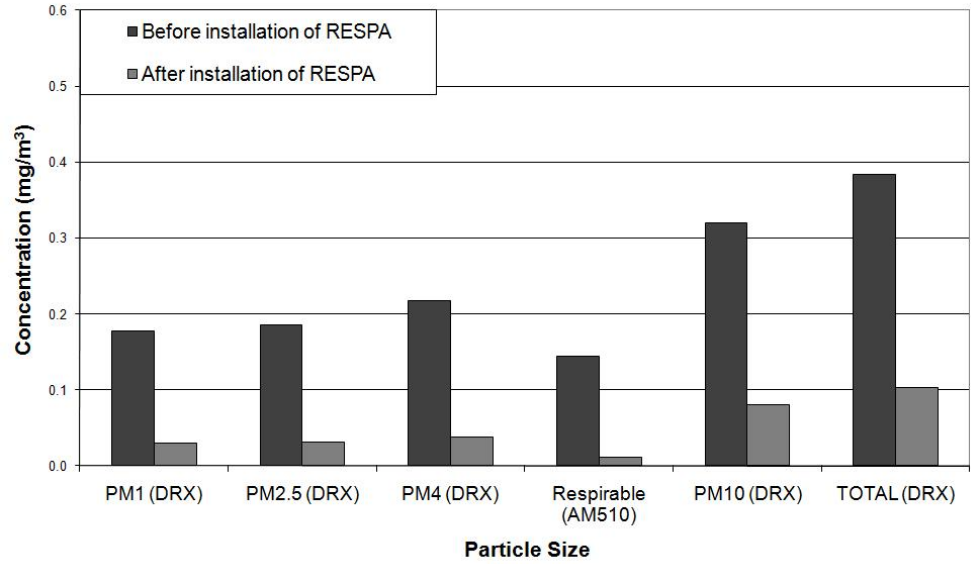


Figure 4.3 Fixed-position monitoring during cutting, confirms that there is an overall reduction in particulate matter and respirable crystalline silica once the RESPA SD® unit had been installed.

Fixed and personal exposure monitoring for RCS (in accordance with AS2985-2009) conducted over a shift during cutting and trenching confirmed that there was a real reduction in RCS once the RESPA SD® unit had been installed as shown in Figure 4.5.

Real time monitoring also supported the findings from fixed and personal exposure monitoring is seen in in Figure 4.4.

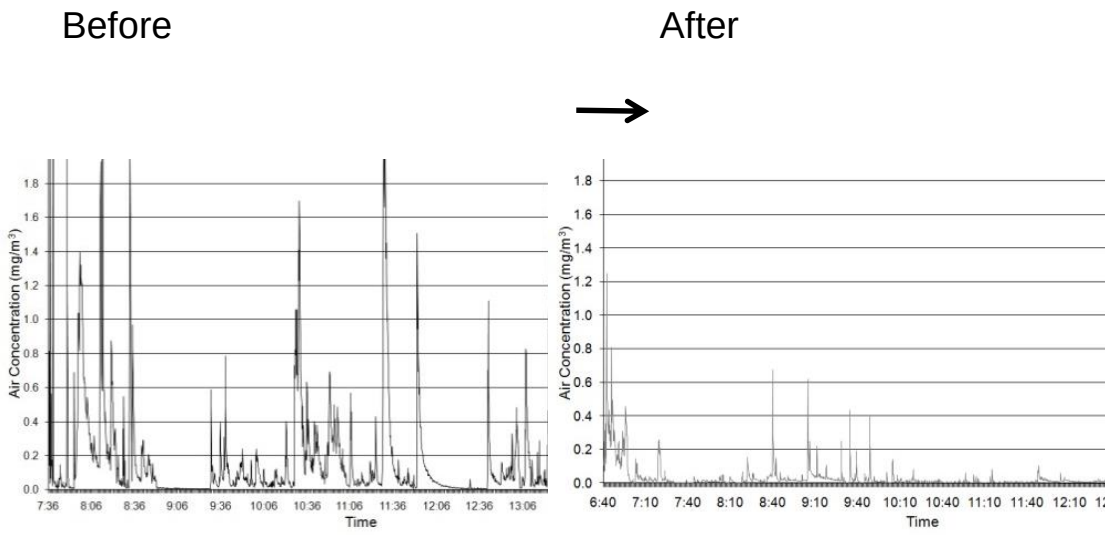


Figure 4.4 Observable reduction in PM_1 concentrations (mg/m³), in real time, measured over six hours during cutting before and after RESPA SD® unit installed.

It was observed that the personal monitoring data for the excavator saw operator is still elevated on one occasion, even with the RESPA SD® unit installed. This is because the operator left the cabin numerous times during the monitoring period which meant that most of the exposure would likely have occurred outside the cabin.

Results recorded from fixed monitors located in the cabin on this same day support the rationale that the exposures occurred outside the cabin (refer to conditions 3 & 6 in Table 4.1 & Figure 4.5).

Table 4.1: Summary of personal and fixed position monitoring results, comparing airborne concentrations of both respirable dust, and RCS, outside, and inside an excavator cabin, before and after installation of a RESPA® and RESPA® recirculation air filtering unit.

Monitoring location	Condition	Description	No.	Respirable dust (mg/m^3) (AS2985-2009) Estimated average (MVUE)	Respirable crystalline silica (mg/m^3) Estimated average (MVUE)
Personal	1	No RESPA®	4	0.53	0.14
Personal	2	RESPA®	3	0.36	0.09
Personal*	3	RESPA® (recirculation)	1	0.27	0.11
Fixed position (inside cabin)	4	No RESPA®	3	0.48	0.12
Fixed position (inside cabin)	5	RESPA®	3	0.12	0.03
Fixed position (inside cabin)	6	RESPA® (recirculation)	1	0.10	0.04
Fixed position (outside cabin)	7	Not applicable	1	2.4	0.83

Generally there was up to a 4-fold reduction of RCS measured inside the cabin once the RESPA SD® (external air) had been installed.

On average the RCS concentration measured inside the cabin (with no RESPA®) was 0.12 mg/m^3. In comparison, once the RESPA SD® (external air) unit had been installed, the average RCS concentration inside the cabin was 0.03 mg/m^3 (refer to Table 4.1, conditions 4 & 5).

The SWA-ES (TWA) reduced limit is 0.09 mg/m^3 (AIOH 2009; Simtars, nd). The SWA-ES (TWA) has been reduced because workers typically work longer than 8-hours. The SWA-ES has been reduced accordingly from 0.1 mg/m^3 to 0.09 mg/m^3 (refer to Section 3.3.5).

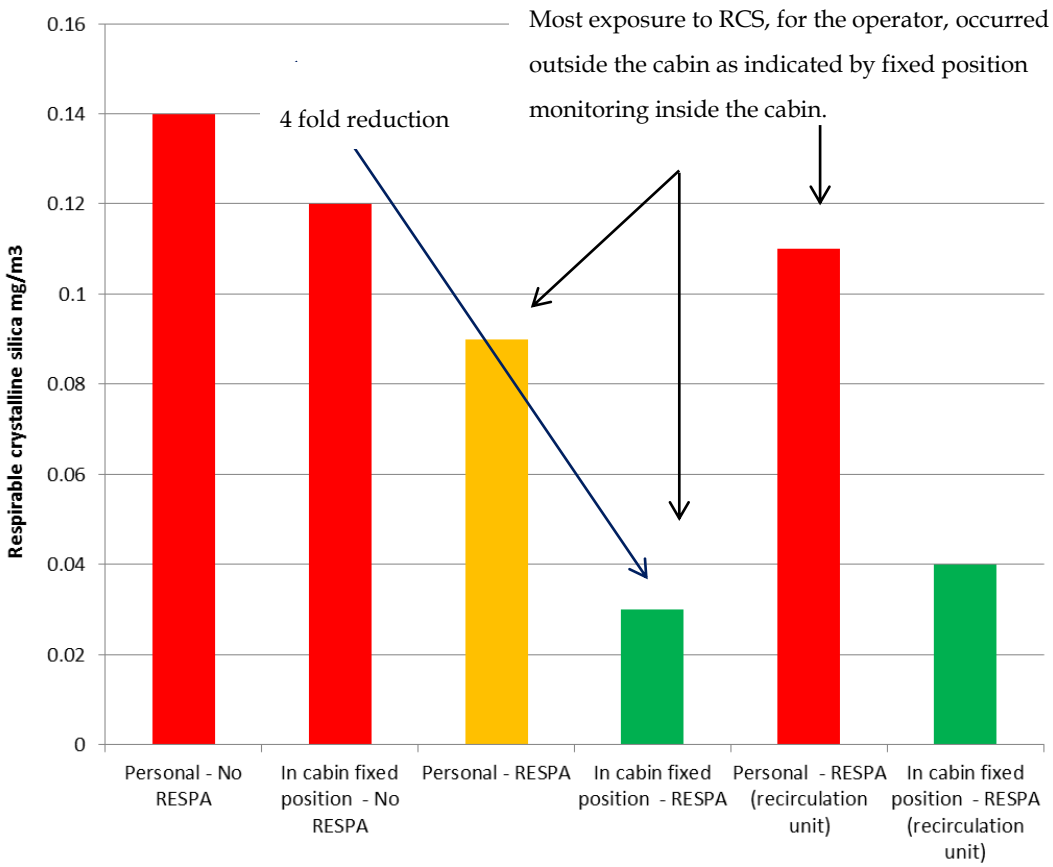


Figure 4.5 Graphical representations showing the concentration of respirable crystalline silica before and after installation of a RESP® (measured using AS2985-2009).

A second RESPA SDX® (recirculation air) unit was installed to remove particulate matter that enters the cabin when the operator enters or exits the cabin or opens doors and windows. Results from this trial did not demonstrate any additional reduction from installing a second unit to filter re-circulated air. However this monitoring was only conducted over a single shift. During this shift the operator was estimated to have exited the cabin on up to sixty (60) occasions (*refer to Table 4.1, condition 3). On the day of monitoring respirable dust and RCS concentrations outside of the cabin were excessive (2.4 mg/m^3 & 0.83 mg/m^3 respectively, Table 4.1, condition 7). These are not typical of the conditions experienced during other stages of the trial. To determine the effectiveness and benefits of installing a second RESPA® unit further monitoring needs to be conducted. Further investigation is required. A more detailed description is provided in Chapter 6 which presents results from electron microscopy analysis.

4.4 Conclusion from RESPA® trials

The DME, Queensland Australia (2009a), demonstrated that there is a high reliance on mobile equipment and crusher cabins to provide an effective barrier to RCS, especially the very fine particles that are most hazardous to health. Many crushing and screening plants are mobile and are not fitted with dust extraction units, though have been fitted with filtered air conditioning systems. These air conditioning systems still allow significant intrusion of RCS into the cabin because the air conditioning filters are not designed to effectively remove very fine particles. This study demonstrated that an excavator cabin fitted with a typical air-conditioning and filtration system does not effectively reduce ingress of respirable dust hence exposing the operator to RCS exposures higher than the SWA-ES. Workers are not adequately protected when working in cabins due to poor cabin door seals and inadequate filtration of the air conditioning systems. Installation of an RESPA® motorised pre-cleaner, filter and pressuriser unit, which puts the cabin under positive pressure, is shown to reduce airborne dust inside the cabin. The degree of dust reduction depends on the particle size being measured. There was at least an order of magnitude reduction for PM_1, the most penetrating particle size. The data collected in this study indicates that the RESPA® PFP filter (MERV 16+) will reduce exposures to RCS for operators working in cabins and control rooms on mobile and fixed plant in the mining and quarrying industry. The RESPA® unit reduced exposure to RCS when fitted to an excavator cabin and saw cabin. Further testing is required to demonstrate whether installing a second unit for recirculated air is warranted where residual dust may accumulate inside the cabin which may then subsequently become airborne. The efficacy of this equipment also needs to be tested on other quarry plant cabins. Preliminary data indicate that installation of these units would be beneficial to the health of machinery operators. For all results specific to the RESPA® trial study refer to Table 4.2 as follows:

Table 4.2 RESPA® study tabulated results.

Date	Location	Activity	Machine	Treatment	Respirable dust (AS2985) mg/m³	Respirable alpha quartz mg/m³	Total dust DRX mg/m³	Respirable dust AM510 mg/m³	PM_{10} DRX mg/m³	PM_4 DRX mg/m³	$PM_{2.5}$ DRX mg/m³	$PM_{1.0}$ DRX mg/m³
18.03.09	Personal	Trenching	CAT330 Exc + saw	None	0.72	0.16						
18.03.09	Static cabin	Trenching	CAT330 Exc + saw	None	0.80	0.20		0.73				
26.03.09	Personal	Trenching	CAT330 Exc + saw	None	0.56	0.15						
27.07.09	Personal	Cutting	Hitachi Exc + saw	None	0.40	0.12						
27.07.09	Static cabin	Cutting	Hitachi Exc + saw	None	0.24	0.07	0.38	0.13	0.32	0.22	0.18	0.18
28.07.09	Personal	Trenching	Hitachi Exc + saw	None	0.43	0.12						
28.07.09	Static cabin	Trenching	Hitachi Exc + saw	None	0.39	0.10	0.50	0.26	0.41	0.26	0.22	0.21
31.07.09	Personal	Cutting	Hitachi Exc + saw	RESPA	0.64	0.17						
31.07.09	Static cabin	Cutting	Hitachi Exc + saw	RESPA	0.18	0.03	0.10		0.08	0.04	0.03	0.03
19.10.09	Personal	Trenching	Hitachi Exc + saw	RESPA	0.28	0.04						
19.10.09	Static cabin	Trenching	Hitachi Exc + saw	RESPA	0.07	0.02	0.09	0.01	0.06	0.03	0.03	0.03
20.10.09	Personal	Trenching and cutting	Hitachi Exc + saw	RESPA	0.16	0.06						
20.10.09	Static cabin	Trenching and cutting	Hitachi Exc + saw	RESPA	0.10	0.03		0.02				
22.10.09	Personal	Trenching	Hitachi Exc + saw	RESPA + recirculation RESPA	0.27	0.11						
22.10.09	Static cabin	Trenching	Hitachi Exc + saw	RESPA + recirculation RESPA	0.10	0.04		0.02				
22.10.09	Static outside cabin	Trenching	Hitachi Exc + saw	RESPA + recirculation RESPA	2.4	0.83						
Safe work exposure standard (8hrs TWA)						**0.10**						
Safe work exposure standard (reduced for extended shifts)						**0.09**						

CHAPTER 5 Exposure and lung-function test results

5.1 Introduction

In Chapter 4 it was demonstrated that air-conditioned cabins in mining excavators allowed ingress of high levels of mine dust containing RCS, unless fitted with filtration systems that screened very fine airborne particulate matter. Cabins also had to be operated under positive air pressure to reduce the exposure risk. As there are many SEG's for excavator drivers in mining sites and quarries, it is important that worker exposure to RCS, as measured in the breathing zone of workers, be measured regularly and under different operating conditions to quantify the risk of adverse lung health.

This chapter explores the risk of exposure to RCS in a range of SEG's in nine sites including quarries and dimension stone sites in Queensland, Australia.

Health surveillance is an integral part of an occupational health and dust exposure management and SWA (2013c) requires baseline and ongoing lung function testing for workers exposed to RCS. This chapter also evaluates exposure to RCS and compares average exposures for similar exposure groups (job types) with the SWA-ES. This is done to determine how often this occupational exposure limit (OEL) is being exceeded. A comparison is made between exposures, and loss of lung function, to see if reduced lung function correlates with increased RCS exposure and whether there is an observable loss of lung function at the SWA-ES.

Feedback from respiratory questionnaires is also assessed especially for those workers with abnormal spirometry to see if symptoms reported align with lung function test results.

5.2 Study sites, rock type at each site and coding for sites and workers

As part of the study design nine sites throughout the northern, central and southern regions of Queensland were selected.

In addition, sites were selected to obtain a cross section of rock type with low to high silica content as shown in Table 5.1. Based on the geology, dimension stone mines (predominantly sandstone) and sand processing plants are considered high, aggregate soil, and gravel (mixed) were considered medium and basalt is considered low. This will allow comparison of relatively high RCS exposures in some exposure groups, with low levels of exposure in other worker groups. It will also enable comparison of exposure with lung function.

Table 5.1 Site codes, rock type description, regions and approximate silica content at each site.

Study site code	Operation	Region	Silica content
A	Dimension sandstone mine	South	High
RS	Dimension sandstone mine	South	High
P	Sand, soil and gravel	North	High
FV	Aggregate, rock and sand (andesite).	Central	Medium
Y	Hornfels and basalt rock	Central	Low
HW	Aggregate	Central	Unknown
FD	Sand, soil and gravel	Central	Medium
C	Sand processing, screening plant	South	High
NS	Sand processing, screening plant	South	High

Workers at each work site were fitted with personal exposure monitors (PEM's) and monitored for full shifts where possible. Based on the job type, workers have been de-identified and allocated into similar exposure groups shown in Table 5.2.

The first letter of the descriptor identifies the site, the number is the worker followed by the job description.

Table 5.2 Site codes and corresponding SEG (job type) codes monitored at each site.

Study site code	Worker code / SEG
A	A1 Loader, A2 Stonemason, A3 Excavator and saw, A5 Saw operator, A6 Fitter.
RS	RS1 Excavator / loader, RS2 Excavator and saw, RS3 Workshop saw, RS4 Workshop saw / forklift, RS5 Electrician, RS6 Fitter.
P	P1 Excavator driver / plant operator, P2 Loader driver / crusher, P3 Loader driver, P 4 Loader driver, P5 Service man.
FV	FV1 Loader, FV2 Crusher operator, FV3 Loader driver / crusher, FV4 Excavator.
Y	Y1 Crusher operator, Y2 Excavator, Y3 Loader, Y4 Loader, Y5 Loader.
HW	HW1 Excavator and crusher, HW2 Bulldozer, HW3 Loader.
FD	FD 1 Crusher, FD 2 Loader, FD 3 Loader / crusher, FD 4 Loader, FD 5 Loader.
C	C1 Plant operator, C2 Plant operator, C5 Plant operator, C3 Loader operator, C4 Fitter,
NS	NS1 Wet plant, NS 2 Wet plant, NS3 Environmental officer, NS4 Dry plant, NS5 Fitter, NS6, NS7 Loader,

5.3 Statistical analysis methodology

The estimated average calculated as the MVUE was considered the best measure to compare with lung function as health effects are related to dose. Dose is defined as being the amount of agent absorbed, taking into account the amount of RCS reaching the lungs, the deposition in the lung and duration of exposure (Edwards et al. 2013). To obtain a best estimate of the average exposure (MVUE) and best estimate of distribution, results <LoQ have been censored. Upper confidence limits (UCL) (lands exact) have been calculated along with geometric standard deviations (GSd.) to get an idea of variability within each SEG data set. The occupational hygiene statistical analysis shown in Table 5.3 was carried out using the American Industrial Hygiene Association (AIHA) statistical package IHSTAT®.

A comparison has been made of each workers exposure to RCS and the number of occurrences of over-exposure as denoted by N > SWA-ES in Table 5.3. The number of smokers or former smokers is provided along with lung function test results.

Measures of lung function (or lung health) include:

- FEV_1 (Forced Expired Volume in 1 Second) measured in Litres, which is the volume of air exhaled in the 1st second (% of predicted).
- FVC (Forced Vital Capacity) measured in Litres, which is the total amount of air exhaled (% of predicted).
- FEV_1/FVC is the ratio of the two measures (%) and provides an indication of airflow obstruction (% of predicted).

To calculate estimated averages (as MVUE), results less than the limit of quantitation (LoQ) were censored (*) using the NDExpo® tool.

This means more robust statistical averages and confidence intervals. Many tools including IHSTAT® do not allow handling of results < LoQ. As a consequence what has traditionally happened is that results < LoQ are replaced with LoQ/2 or LoQ/√2. This method causes bias in the interpretation. NDexpo® is an improvement on conventional methods.

NDExpo® uses regression analysis and is based on fitting detected values to a log-normal distribution, and then predicting a replacement value for each value <LoQ value as a function of the fitted distribution and their rank among detected values. Each value < LoQ ends up replaced by a prediction and then processed by IHSTAT as if there are no results < LoQ (Lavoue 2015).

According to Lavoue (2015 p.1),

> 'this approach compares well with other methods such as maximum likelihood, and represents a significant improvement over simple imputation'

To obtain a clearer picture of the potential risk of RCS to health, further analysis was undertaken to compare the MVUE with the loss of lung function measured as FEV1 % of predicted and FEV1/FVC % of predicted.

The data analysis add-in feature of Excel® was used to evaluate the correlation for both linear and curvilinear curves to determine the curve of best fit. Excel® allows analysis of the Kolmogorov goodness of fit tests (Miller & Miller 1984) and also calculation of probability of correlation of log-transformed values and determines whether in fact the correlation coefficient calculated was significant (Miller & Miller 1984).

5.4 Personal exposure monitoring description and results

Estimated average concentrations of RCS collected on filters of PEM's are shown in Figure 5.1.

When statistical analysis was performed for each of the similar exposure groups (SEGs) tested, at least four of the fifteen SEG average exposures were above the SWA-ES, while eight had a maximum exposure above the SWA - ES.

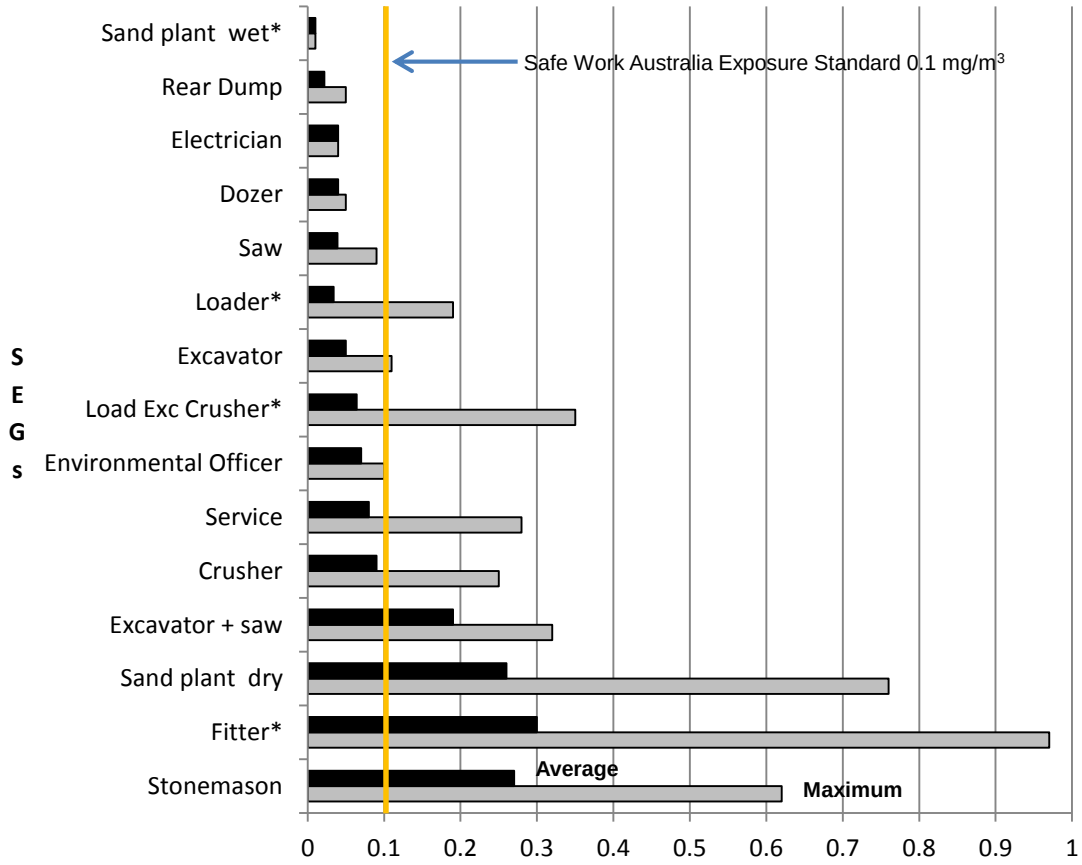


Figure 5.1 Estimated average and maximum concentrations of respirable crystalline silica for similar exposure groups (SEGs), as measured in the breathing zone of workers.

5.5 Personal exposure monitoring and lung health test results.

Table 5.3 provides a summary of results for all similar exposure groups.

The number of workers tested for each SEG, and data for lung function and estimated average RCS exposures are shown. These are the worker SEG exposure levels if respiratory protective equipment (RPE) is not used.

Similar exposure groups (SEG) have been highlighted where at least 6 RCS samples (# samples) have been taken, at least 2 workers in the SEG, and the estimated average exposure range is between 0.01 – 0.20 mg/m^3.

Where SEGs have been denoted with (*) this means that some individual results in data set for the SEG are less than the limit of quantitation (LoQ).

An assessment of log-normality is also provided, and LN indicates that the exposure group has a log-normal distribution. Where insufficient samples (IS) are noted, this means that a sufficient number of samples (≥ 5) has not been taken to make a determination to confidently calculate the UCL.

SEGs have further been grouped into three groups as high (A), medium (B), and low (C) exposure bands for follow up statistical analysis using Analysis Of Variance (ANOVA).

Table 5.3 Summary results table for RCS similar exposure group (SEG) and lung function test results.

SEG	Estimated average (MVUE) respirable dust mg/m³	Estimated (MVUE) average RCS mg/m3	UCL (Lands Exact) 95%	Max RCS mg/m3	# samples	GSd	LN	# workers	N > SWA-ES#	# smokers or former	FVC % of pred	FEV 1 % of pred	FEV1/FVC % of pred	Group
Stonemason	0.83	0.27	IS	0.62	3	3.9	IS	1	1	0	83	72	85	
Fitter*	0.60	0.30	7.2	0.97	11	6.5	Yes	4	2	3	92	86	95	
Sand plant dry	0.40	0.26	0.35	0.76	13	1.6	Yes	4	3	1	90	92	102	
Excavator + saw	0.49	0.19	0.62	0.32	7	2.3	Yes	3	2	2	98	73	76	A
Crusher	0.64	0.09	0.14	0.25	9	1.7	No	3	1	1	87	79	92	A
Service	0.38	0.08	IS	0.28	5	3.0	Yes	2	1	1	97	84	87	
Environmental Officer	0.21	0.07	IS	0.1	3	1.5	IS	1	0	0	88	86	99	
Load / Exc / Crusher*	0.83	0.06	0.37	0.35	11	3.9	Yes	4	1	3	91	88	96	B
Excavator	0.23	0.05	0.08	0.11	12	1.8	Yes	4	1	3	92	83	92	B
Loader*	0.25	0.04	0.05	0.19	32	2.3	Yes	11	2	10	89	84	95	B
Saw	0.84	0.04	0.08	0.09	9	1.8	Yes	3	0	3	82	81	99	B
Dozer	0.34	0.04	IS	0.05	3	IS	IS	1	0	1	77	67	87	
Electrician	0.3	0.04	IS	0.04	2	IS	IS	1	0	1	101	98	98	
Rear Dump	0.16	0.02	0.03	0.05	8	1.9	Yes	3	0	3	89	90	97	C
Sand plant wet*	0.07	0.01	0.01	0.01	6	*	*	2	0	1	109	103	94	C
Total					134			47	14	33				
Estimated average	0.45	0.09				2.5	Yes				91	91	93	
% smokers or former										70				

# possible restrictive	3
% possible restrictive	7
# possible obstructive	15
% possible obstructive	33

% > OEL 30%

5.6 Statistical analysis and discussion.

When statistical analysis was performed for each similar exposure group (SEG), four of the fifteen SEG average exposures were above the weekly adjusted SWA-ES while eight had a maximum exposure above the weekly adjusted SWA-ES (Figure 5.1 & Table 5.3).

Of the forty seven workers monitored, fourteen (or 30%) had RCS exposures that exceeded the weekly adjusted SWA-ES.

When statistical analysis is carried out, log-normality is demonstrated when NDexpo® is used on SEGs with results < LoQ.

Data for nine SEGs were log-normally distributed and most had geometric standard deviations less than 2.5 which indicated that the data were representative of typical exposures for most SEGs.

5.6.1 Respirable crystalline silica (RCS) exposures correlated with loss of lung function.

When all of the data were analysed, as shown in Figure 5.2, there appeared to be a downward trend up to 0.2 mg/m^3. For higher exposures above 0.2 mg/m^3 the same trend was not observed for two of the data points (two points are circled in Figure 5.2). These points were recorded for fitters and sand plant operators respectively.

Due to the high variability for FEV1 % of predicted and range of exposures around the RCS exposure average for the Fitter and Sand Plant Operator most of the statistical analysis is focussed on SEGs with an exposure < 0.2 mg/m^3.

Further discussion is provided at the end of this chapter.

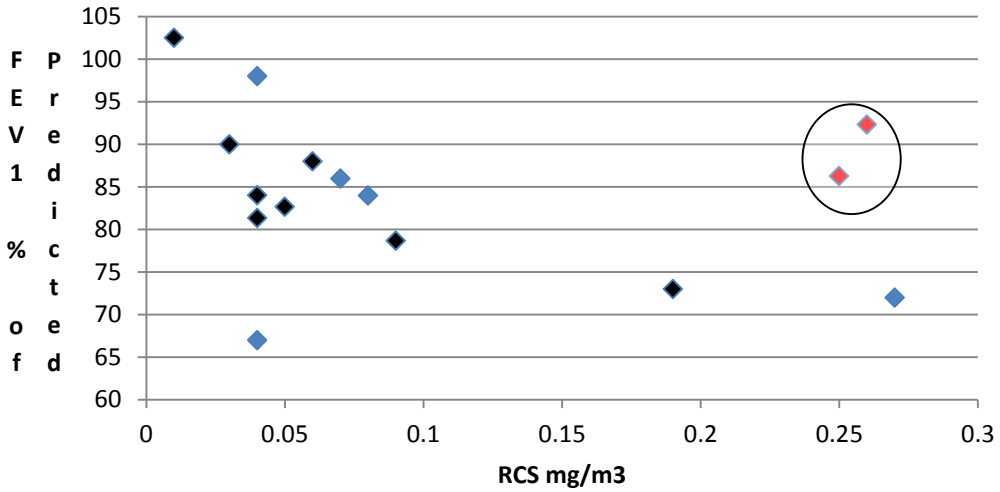


Figure 5.2 Estimated (MVUE) full shift exposures pooled for each SEG correlated with lung function measured as FEV1 % of predicted.

To obtain a clearer picture of the potential risk of RCS to health at concentrations < 0.2 mg/m^3, further analysis was undertaken to better define the exposure profile by comparing specific SEGs against loss of lung function (Figure 5.2). These MVUE are compared with the loss of lung function measured as FEV1 % of predicted (Figure 5.3) and FEV1/FVC % of predicted (Figure 5.4). To improve accuracy, the correlation has only been plotted for those SEGs < 0.2 mg/m^3 RCS, with at least 6 samples and where at least 2 workers are in a SEG as shown in Table 5.2 highlighted in yellow. When the data were re-analysed (shown in Figures 5.3 and 5.4) as discussed, the correlation between exposure to RCS and loss of lung function was significant ($p<0.05$).

Figures 5.3 and 5.4 demonstrate the relationship between RCS exposure and loss of lung function. Although the analysis shows a positive correlation it is not a linear function. The functions shown in Figures 5.3 and 5.4 are curvilinear. The arrow seen in Figure 5.3 is at the SWA-ES (8hr-TWA) which is 0.1 mg/m^3. The goodness of fit test has demonstrated that both curves shown in Figures 5.3 and 5.4 are significant ($p<0.05$). Furthermore a trend test using SAS 9.4 resulted in $p = 0.0013$.

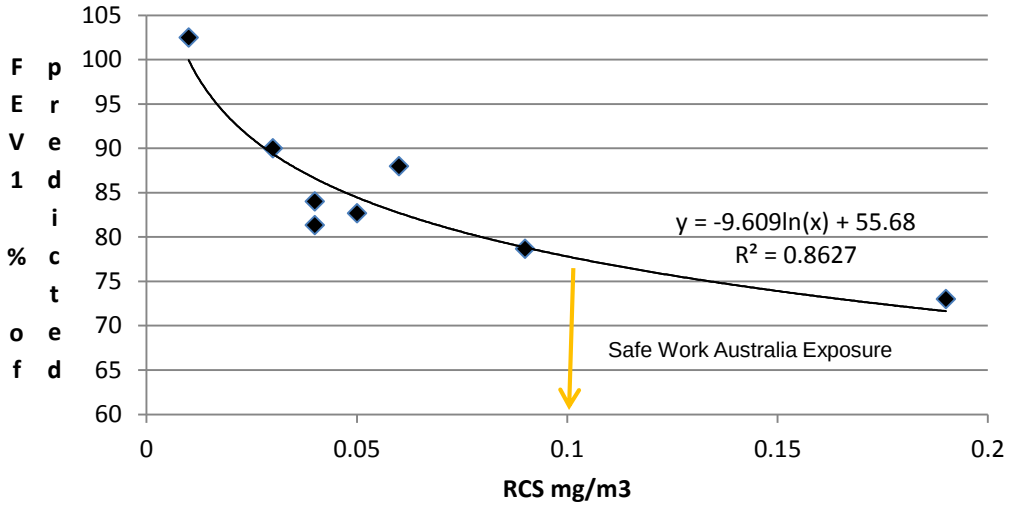


Figure 5.3 Estimated (MVUE) full shift exposures pooled for each SEG < 0.2mg/m³ with 6 or more RCS samples (refer to appendix K), correlated with lung function measured as FEV1 % of predicted (p<0.05 as confirmed by the Kolmogorov goodness of fit test).

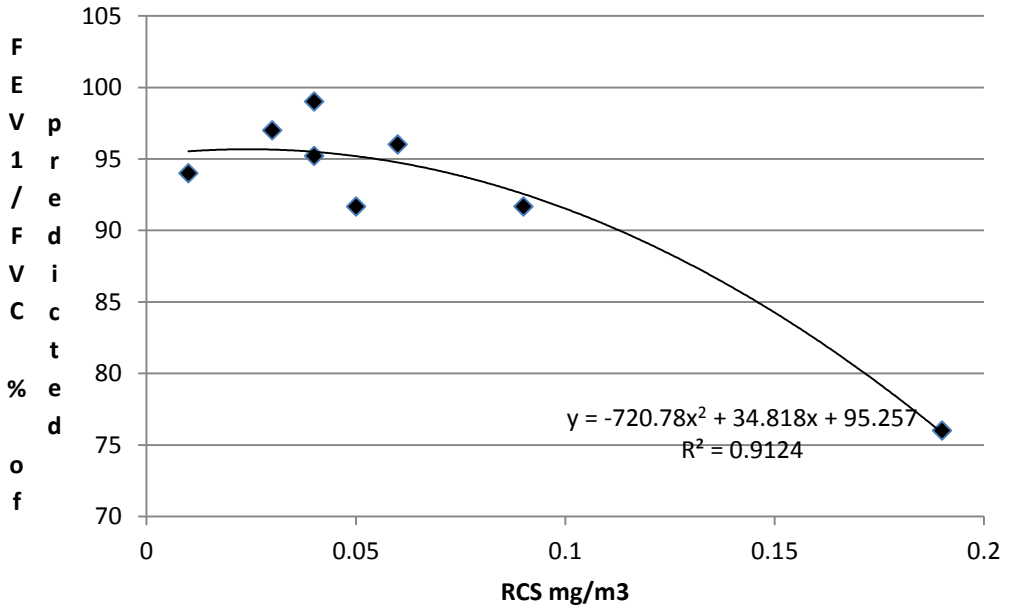


Figure 5.4 Correlation between FEV1/FVC % of predicted and minimum variance unbiased estimate (MVUE) full shift exposures pooled for each SEG < 0.2mg/m³ with more than 6 RCS samples (p<0.05 as confirmed by the Kolmogorov goodness of fit test).

Although there are downward trends when maximum RCS is compared with loss of lung function measured as FEV1 % of predicted (Figure 5.5) and FEV1/FVC % of predicted (Figure 5.6), findings from the the Kolmogorov goodness of fit test does not demonstrate the same significant fit ($p>0.05$). Figure 5.5 is close to being significant ($p= 0.11$).

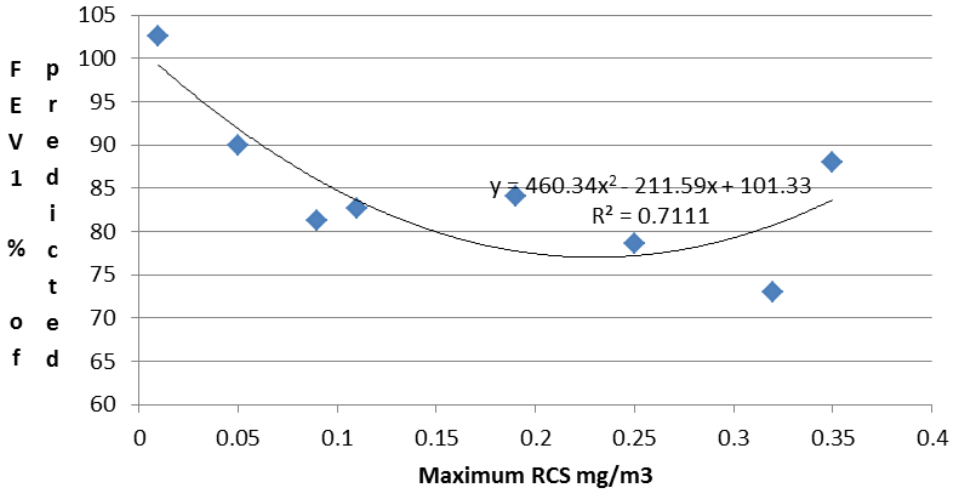


Figure 5.5 Maximum full shift exposures pooled for each SEG < 0.2mg/m³ MVUE with more than 6 RCS samples correlated with lung function measured as FE1 % of predicted (p=0.11 which is close to being significant - Kolmogorov goodness of fit test).

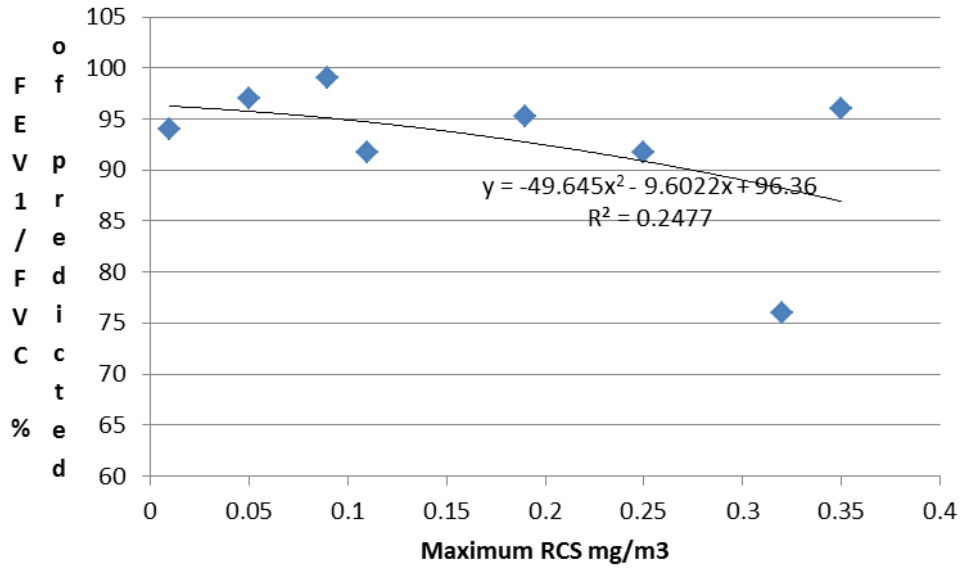


Figure 5.6 Maximum full shift exposures pooled for each SEG < 0.2mg/m³ MVUE with more than 6 RCS samples weakly correlated with lung function measured as FEV1/FVC % of predicted (p>0.05 as confirmed by the Kolmogorov goodness of fit test).

5.6.2 Respirable dust exposures correlated with loss of lung function.

The same highlighted sample results (Table 5.2) were plotted for respirable dust (Figure 5.7). Comparing respirable dust with loss of lung function measured as FEV1 % of predicted, shows a loss of lung function below the lower limit of normal (FEV1 % of predicted = 80) at about 0.4 mg/m^3 of respirable dust. The results indicate that FEV1 % of predicted is a sensitive measure when correlating respirable dust and RCS with loss of lung function.

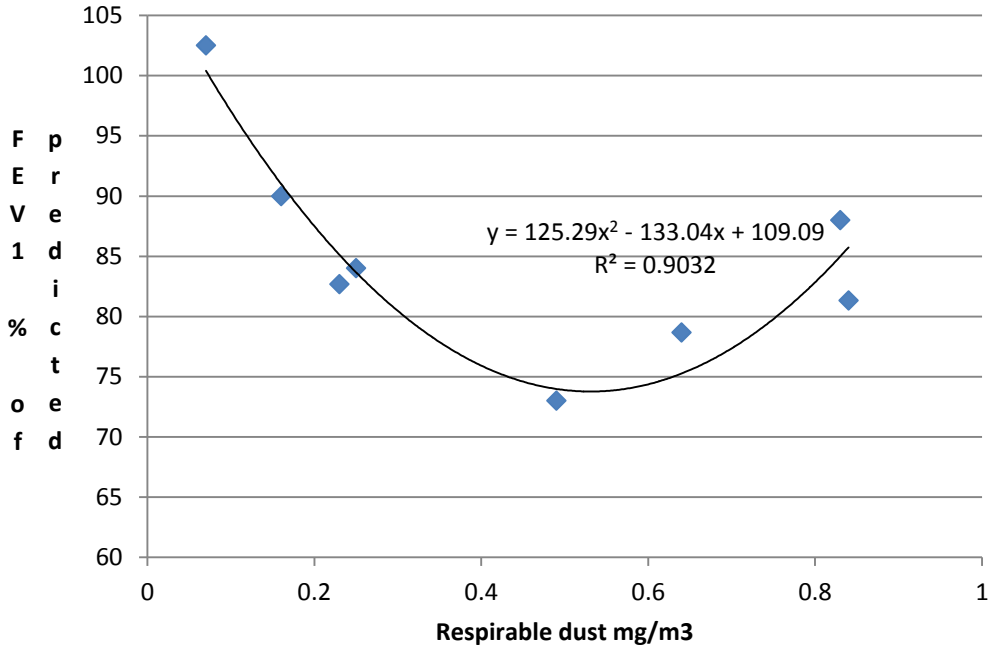


Figure 5.7 Full shift estimated average exposures (MVUE) for respirable dust pooled for each SEG for all samples correlated with lung function measured as FEV1 % of predicted.

5.6.3 Analysis of variance (ANOVA).

To determine if there is a significant difference between exposures of similar exposure groups (SEGs) to RCS, natural log (LN) transformed mean confidence intervals were calculated and compared using Minitab® as shown in Figure 5.8.

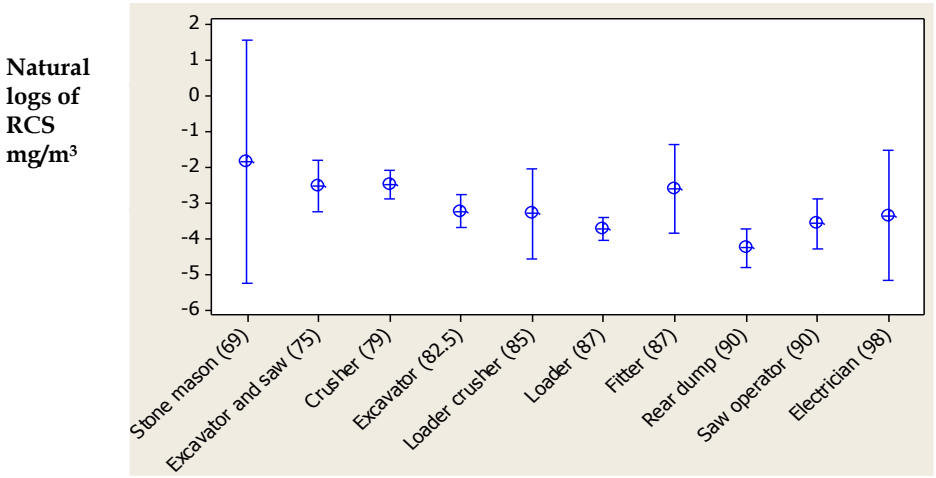


Figure 5.8: Natural log transformed values comparing arithmetic means and 95 confidence intervals for each similar exposure group RCS exposure. The number in brackets is the average maximum FEV1 % of predicted (with 95% confidence intervals).

The average RCS concentrations differed between SEGs specifically for the crusher operator, excavator operator and loader operator (Figure 5.8). When additional analysis was carried out to determine confidence intervals around the mean FEV1 % of predicted, there was no significant difference (Figure 5.9).

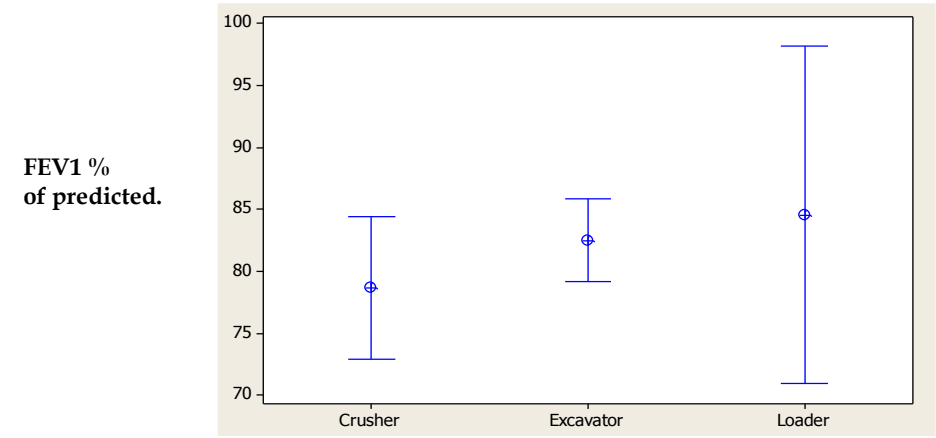


Figure 5.9: Average maximum FEV1 % of predicted and confidence intervals for the crusher, excavator and loader operators (with 95% confidence intervals).

To verify whether there is a real difference in RCS exposure between SEGs, analysis of variance (ANOVA) was undertaken for all measured exposures. The analysis demonstrated that there was a significant difference ($p=0.0007$, $df = 9$) between all SEGs for RCS exposure. A further analysis for 3 SEGs, crusher, excavator and loader showed a significant difference ($p=0.0005$, $df = 2$) between RCS exposures. The ANOVA analysis for FEV1 % of predicted did not show a similar significant difference between SEGs ($p=0.824$, $df = 2$) but the crusher and the excavator operators approached significance ($p=0.069$, $df = 2$) (Figure 5.9).

The data were further analysed to understand why a similar difference in lung function between SEGs cannot be demonstrated. The quality of spirometry is important and the Easyone® spirometer provides a quality score after each assessment (Table 5.4). An A reading test result corresponds to a good quality (precise) assessment whereas F is sub-standard.

Table 5.4 Quality reading of lung function test results.

Quality reading	Number
A	25
B	9
C	3
D	5
F	2

According to the EasyOne™ spirometer manual (ndd Medical Technologies, 2010, readings A – C are acceptable and give reproducible results whereas reading D provides 2 acceptable results although not reproducible and reading F means that the test is not acceptable. Most spirometry tests had quality scores of A – D. Therefore the spirometry test results are valid.Analysis of variance was carried out for SEGs that had acceptable quality spirometer results for RCS exposure and where there were at least 3 workers in each SEG to account for inter-individual variability.

For a significant difference to be demonstrated, the F value must be > than F critical and the p-value must be < 0.05. Larger sample sizes are preferred because as sample size increases the more precise the estimate is of inter-individual variability. ANOVA failed to show a significant difference between FEV1 % predicted for each SEG as shown in Table 5.5.

Table 5.5: ANOVA carried out for FEV1 % of predicted for SEGs with at least 3 different workers.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Crusher	3	236	78.66667	5.333333
Excavator	4	330	82.5	4.333333
Loader	9	760	84.44444	311.2778

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	75.86111	2	37.93056	0.196149	0.824278	3.805565
Within Groups	2513.889	13	193.3761			
Total	2589.75	15				

5.6.4 Grouping of data for improved analysis of variance (ANOVA).

To strengthen the ANOVA similar exposure groups were grouped into three distinct bands. This approach was loosely based on the model provided by the Multi-Centre Case-Control Study in Europe (Cassidy et al. 2007) which compared cumulative exposure estimates for RCS grouped as tertiles. Cassidy et al. (2007) grouped the exposures as low <0.05 mg/m^3, medium <0.05 – 0.2 mg/m^3 and high > 0.2 mg/m^3. In this study the RCS exposures and lung function test results were pooled into 3 RCS exposure bands (ranges) (as shown in Table 5.6) to increase the statistical power for ANOVA. The groups were low (group C) < 0.04 mg/m^3, medium (group B) ≥ 0.04 - ≤ 0.08 mg/m^3, and high (group A) ≥ 0.09 - ≤ 0.20 mg/m^3.When RCS results are pooled for groups A&B, the NDexp® method was used to censor results < LoQ for both of these groups.

Group C had exposures that were at, or close, to the LoQ. The method used to censor these results replaced each <LoQ value with LoQ/SQRT 2. This is known as substitution (Ganser & Hewett 2010). In addition as distributions for groups A&B were shown to be log-normal whereas group C was not. Therefore upper and lower confidence limit values cannot be determined for group C**.Considering information provided Hewett and Ganser (2007), imputation for group C was not justified, therefore substitution was used instead. As goups A & B were shown to be log-normally distributed, imputation using a method known as log-probability regression (LPR) was carried out using NDexp® (Ganser & Hewett 2010).

Table 5.6 indicates marked differences between the RCS ranges and shows that there is reduced lung function capacity as the RCS range (or exposure band) increases. ANOVA between the three groups is carried out to confirm that these differences, for both FEV1 % of predicted and RCS, are real and unlikely to occur by chance. Grouping data showed significant differences ($p<0.05$) between groups A, B and C for both RCS mg/m^3 and FEV1 % of predicted as shown in Table 5.7 and Table 5.8 respectively.

Table 5.6 Grouping SEGs to improve ANOVA

Group	Similar exposure groups	Range of estimated average RCS exposures mg/m^3	Estimated average MVUE mg/m^3	UCL LCL (GSd)	Average maximum FEV1 % of predicted	UCL LCL (GSd)
A	Excavator + saw Crusher	≥ 0.09 - ≤ 0.20 mg/m^3	0.132	0.20 0.10 (2.0)	76	87 68 (1.2)
B	Loader/excavator crusher Excavator Loader Saw	≥ 0.04 - ≤ 0.08 mg/m^3	0.043	0.06 0.04 (2.4)	84	89 80 (1.2)
C	Rear dump Sand plant wet	< 0.04 mg/m^3	0.02**	**	95	107 86 (1.1)

Table 5.7 ANOVA for RCS for groups A, B, C

SUMMARY

Groups mg/m³	*Count*	*Sum*	*Average*	*Variance*
≥ 0.09 ≤ 0.20 (A)	16	2.11	0.13187	0.008896
≥ 0.04 ≤ 0.08 (B)	64	2.94	0.04594	0.002504
< 0.04 (C)	14	0.33	0.02357	7.09E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.11317	2	0.05659	**17.62809**	3.38E-07	**3.096553**
Within Groups	0.29211	91	0.00321			
Total	0.40528	93				

Table 5.8 ANOVA for FEV1 % of predicted for groups A, B, C

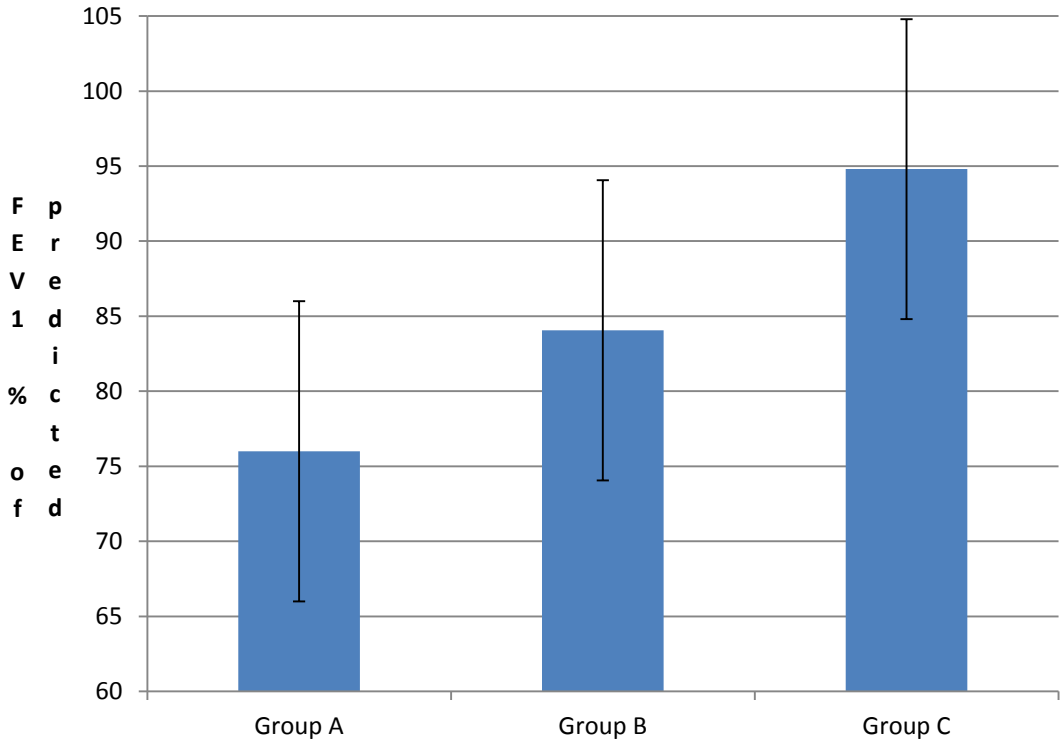
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
76 (UCL 87 LCL 68) A	6	456	76	128
84 (89 UCL 80 LCL) B	18	1511	84	144
95 (107 UCL 86 LCL) C	5	474	95	121

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	966	2	483	**3.519**	0.044	**3.369**
Within Groups	3570	26	137			
Total	4536	28				

Figure 5.10 demonstrates how grouping the data has separated out the distributions for each data set.



Exposure bands RCS mg/m³.

(**Group A - high**: ≥ 0.09 - ≤ 0.20 mg/m³) (**Group B – medium** ≥ 0.04 - ≤ 0.08 mg/m³) (**Group C – low <** 0.04 mg/m³)

Figure 5.10 Average maximum FEV1 % of predicted for each group.

Applying the Shapiro-Wilk test for normality to the data has confirmed that groups A, C and D as shown in Figure 5.10 are all normally distributed ($p < 0.05$). A t-Test (Table 5.9) was carried out to further demonstrate that there is a real difference between RCS exposure and dose response as FEV1 % of predicted between Group A (RCS ≥ 0.09 - ≤ 0.20 mg/m³) and Group C (RCS < 0.04 mg/m³).

Table 5.9 t-Test further demonstrating significant difference between Group A (RCS 0.09 – 0.19 mg/m^3) with mean lung function of 76 FEV1 % of predicted and Group C (RCS < 0.04 mg/m^3) with mean lung function of 95 FEV1 % of predicted.

t-Test: Two-Sample Assuming Equal Variances

	Group A (RCS) ≥ 0.09 – ≤ 0.20 mg/m^3	*Group C (RCS)* < 0.04 mg/m^3
Mean loss of lung function (FEV1% of predicted)	**76**	**95**
Variance	127.6	120.7
Observations	6	5
Pooled Variance	124.53	
Hypothesized Mean Difference	0	
df	9	
t Stat	-2.78	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.83	
P(T<=t) two-tail	0.02	
t Critical two-tail	2.26	

Figure 5.11 further demonstrates how loss of lung function measured as FEV1 % of predicted, will likely occur, at the Safe Work Australia Exposure Standard TWA-8hr which is 0.1 mg/m^3.

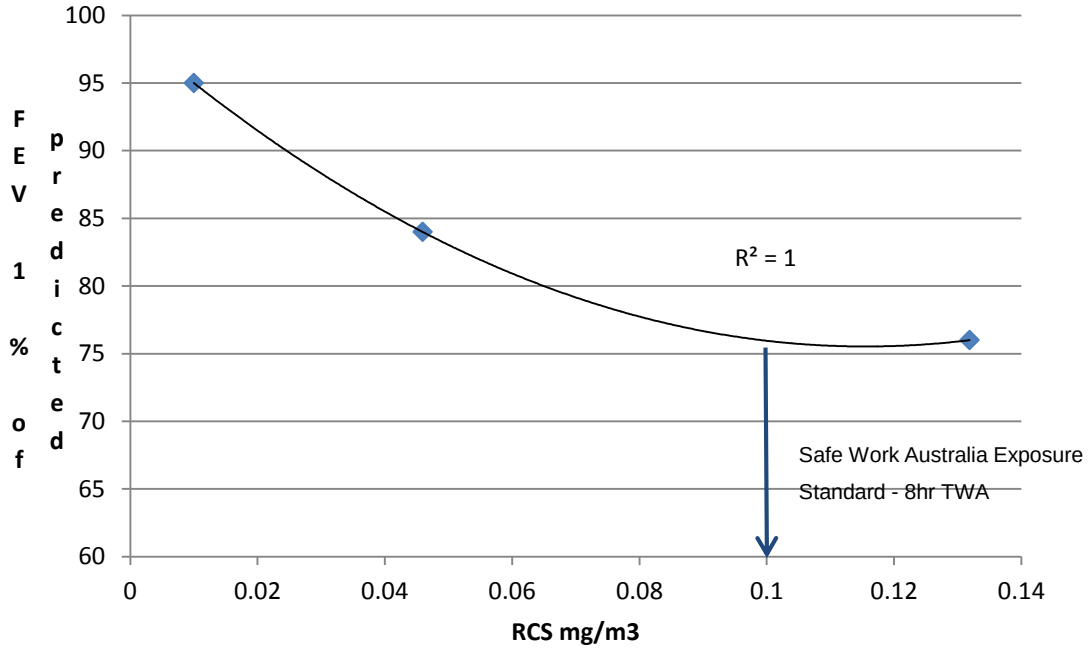


Figure 5.11 Average maximum FEV1 % of predicted for each group correlated with RCS group average exposures.

5.6.5 RCS exposure and lung function test results combined with smoking.

The majority of workers (73%) in this study were smokers, which means that the risk of lung disease will be increased. Therefore further evaluation was carried out (Figure 5.12) where it can be seen that for workers exposed to ≥ 0.04 mg/m^3 of RCS, there were more smokers showing symptoms of obstructive disease. The proportion of smokers showing symptoms was six times higher when compared with non-smokers. This difference was not shown where workers were exposed to RCS < 0.04 mg/m^3. Although COPD can occur for non-smokers exposed to respirable dust and RCS, the combination of exposure and smoking increased the risk beyond that for smoking (Hnizo & Vallyathan 2003). In contrast, Figure 5.13 can be used to compare workers exposed to RCS < 0.4 mg/m^3. From Figure 5.12 it is apparent that more than 50% of smokers exposed to RCS have symptoms of obstructive lung disease whereas the same is not observed for smokers exposed to RCS < 0.04 mg/m^3 (Figure 5.13).

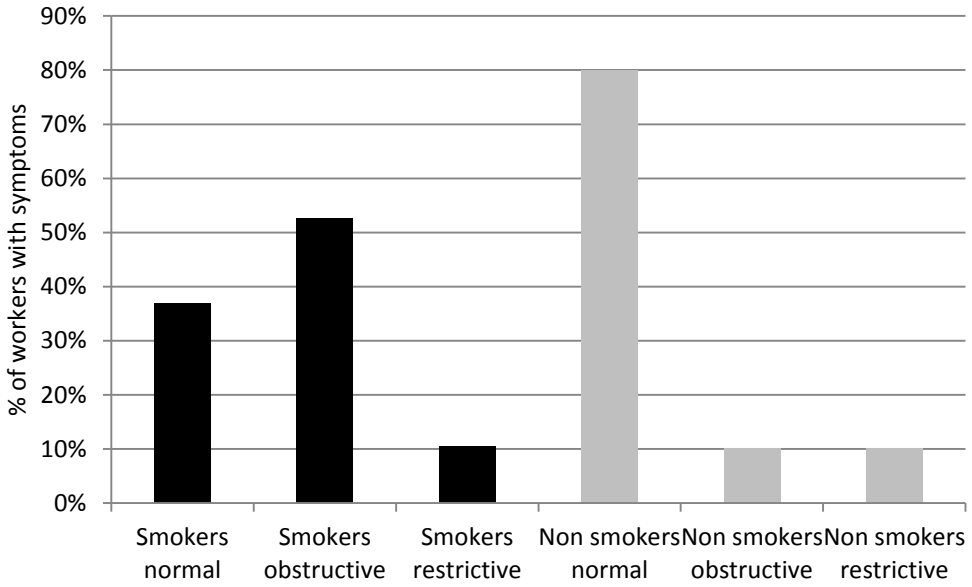


Figure 5.12 Comparison of lung function patterns between smokers and non-smokers where exposure to RCS is ≥ 0.04 mg/m³ silica.

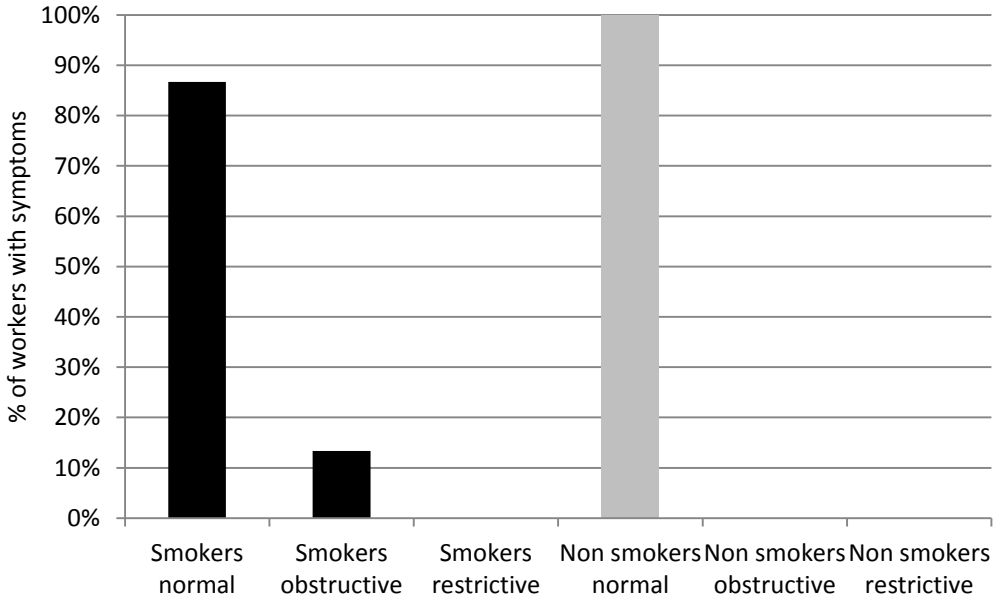


Figure 5.13 Comparison of lung function patterns between smokers and non-smokers where exposure to RCS is < 0.04 mg/m³ silica.

The comparison between workers who do or don't smoke demonstrates the impact that both smoking and RCS exposure have on the increased risk of COPD. There is a marked increase of obstructive lung disease symptoms for workers who smoke and are also exposed to ≥ 0.04 mg/m^3 RCS.

NIOSH (2012c) estimates indicate that at least 15% or more of adult-onset asthma and COPD are due to occupational exposures. Asthma is typically associated with exposure to other hazardous agents such as isocyanates, metals, and working with animals and textiles and not specifically from being exposed to RCS (NIOSH 2012c). COPD on the other hand, especially emphysema has been shown to occur from exposure to RCS (Hnizdo & Vallyathan 2003).

5.7 Interpretation of lung function test results.

FEV1/FVC is the first measurement to be evaluated to distinguish obstructive from non-obstructive patterns. When the FEV1/FEVC and FEV1 are both less than the lower limit of normal (LLN), airways obstruction is present (Townsend et al. 2011, p.578).

When FEV1, FVC and FEV1/FVC % of predicted are all low this may indicate both obstructive and restrictive (mixed) lung disease. Where FEV1 % of predicted is reduced (or normal), when FVC is reduced and FEV1/FVC % of predicted is relatively high or normal this indicates restrictive lung disease (Johns & Pierce 2007) as shown in Table 5.10.

Table 5.10 Three classifications for abnormal ventilator function.
(Source: Johns & Pierce 2007, p.57).

Classification of abnormalities by spirometry.			
	Obstructive	Apparent restrictive	Mixed
FEV1	↓	↓ or normal	↓
FVC	↓ or normal	↓	↓
FEV1/FVC	↓	↑ or normal	↓

The FEV1 % of predicted is generally used to grade severity in patients with obstructive, restrictive and mixed pulmonary defects. Pellegrino et al. (2005) provided data which can be used to rate the level of severity (see Table 5.11).

Table 5.11 Severity of any spirometric abnormality based on the forced expiratory volume in one second (FEV1) (Source: Pellegrino et al. 2005, p.957).

Degree of severity	FEV1 % of predicted
Mild	> 70#
Moderate	60 - 69
Moderately severe	50 - 59
Severe	35 - 49
Very severe	< 35

Note: # see discussion on what is considered lower limit of normal (LLN).

Criteria, as shown in Tables 5.10 and 5.11, have been used to assess lung function in this study. Individual test results are shown in Table 5.9. Spirometry print out results and graphs along with lung function symptoms for individuals with moderate loss of lung function severity are presented at the end of this chapter in Figures 5.14 to 5.20. A summary table comparing individual RCS exposure with lung function test results are presented in Table 5.12. Five operators were shown to have obstructive or mixed lung function patterns of at least moderate severity which is indicative of COPD. Two operators show restrictive lung function patterns indicating silicosis. The results from this study concur with the HSE (2015), where FVC or FEV1 % of predicted < 80% is considered an abnormal lung function test result.

Table 5.12 Individual (de-identified) RCS and lung function test results.

Worker code	Site	SEG	RCS mg/m³ Average (maximum)	FVC % of predicted	FEV1 % of predicted	FEV1/FVC % of predicted	Assessment	Smoker	Age
A2	A	Stonemason	0.27 (0.65)	83	72	85	Mild obstruction or mixed	No	35
A3	A	Excavator + saw	0.25 (0.32)	107	62	58	Moderate obstruction	Yes	37
RS2	RS	Excavator + saw	0.15 (0.25)	100	93	93	Normal	No	20
RS3.2	RS	Excavator + saw	0.26	86	65	76	Moderate obstruction or mixed	Yes	44
RS	RS	Excavator	0.11	93	82	87	Normal	Yes	42
P1	P	Excavator	0.08 (0.11)	80	83	104	Normal	No	37
FV	FV	Excavator	0.03 (0.05)	91	85	94	Normal	F	49
Y2	Y	Excavator	0.02 (0.03)	104	80	77	Mild obstruction	Yes	35
A1	A	Loader	0.06 (0.06)	90	80	89	Mild obstruction	Yes	46
P3	P	Loader	0.07 (0.08)	77	69	89	Moderate restriction	Yes	47
P4	P	Loader	0.10 (0.19)	89	86	97	Normal	Yes	50
FV1	FV	Loader	0.04 (0.06)	73	68	93	Moderate restriction	Yes	20
NS7	NS	Loader	0.01 (0.01)	83	90	96	Normal	F	33
CS3	CS	Loader	0.03 (0.04)	83	90	86	Normal	Yes	44
FD4	FD	Loader	0.02 (0.03)	83	91	110	Normal	F	45
FD5	FD	Loader	0.02 (0.03)	80	92	115	Normal	No	49
HW3	HW	Loader	0.02 (0.03)	D	D	D	Failed test	Yes	42
Y3	Y	Loader	0.02 (0.02)	72	58	81	Moderately severe obstruction or mixed	Yes	54
Y4	Y	Loader	0.01 (0.01)	117	113	97	Normal	F	45
FD2	FD	Crusher	0.06 (0.07)	72	76	107	Mild restriction	No	51
Y1	Y	Crusher	0.15 (0.25)	94	80	85	Mild obstruction	Yes	54
P2	P	Load / excavator crusher	0.24 (0.35)	99	103	104	Normal	No	34
FV2	FV	Load / excavator crusher	0.07 (0.07)	95	80	83	Mild obstruction	Yes	32
FD3	FD	Load / excavator crusher	0.06 (0.10)	74	68	91	Moderate obstruction or mixed	F	56
HW1	HW	Load / excavator crusher	0.02 (0.03)	97	103	107	Normal	Yes	41
RS4	RS	Saw	0.03 (0.06)	83	93	111	Normal	Yes	29
A5	A	Saw	0.04 (0.09)	78	86	110	Normal	F	57
HW2	HW	Dozer	0.04 (0.09)	77	67	87	Moderate obstruction or mixed	Yes	45
P5	P	Service	0.13 (0.28)	97	84	87	Mild obstruction	Yes	48
RS5	RS	Electrician	0.04 (0.04)	101	98	98	Normal	Yes	55

Table 5.12 Individual (de-identified) RCS and lung function test results (continued).

Worker code	Site	SEG	RCS mg/m³Average (max)	FVC % of predicted	FEV1 % of predicted	FEV1/FVC % of predicted	Assessment	Smoker	Age
RS6	RS	Fitter	0.08 (0.16)	87	90	93	Normal	Yes	48
A6	A	Fitter	0.09 (0.09)	84	85	101	Normal	No	58
C	C	Fitter	0.78 (0.97)	110	86	78	Normal	Yes	48
NS5	NS	Fitter	0.01 (0.01)	85	84	99	Normal	F	57
NS3	NS	Environment Officer	0.07 (0.10)	88	86	93	Normal	No	19
NS4	NS	Sand plant dry	0.23 (0.32)	110	113	103	Normal	No	63
C	C	Sand plant dry	0.41 (0.76)	96	96	100	Normal	No	23
C	C	Sand plant dry	0.26 (0.37)	92	99	108	Normal	No	24
C	C	Sand plant dry	0.19 (0.22)	83	82	99	Normal	F	40
NS2	NS	Sand plant wet	0.02 (0.02)	118	111	94	Normal	No	63
NS1	NS	Sand plant wet	0.02 (0.02)	100	94	94	Normal	F	25
NS6*	NS	Rear dump	0.01 (0.01)	F	F	F	Failed test	Yes	35
FD1**	FD	Rear dump	0.04 (0.05)	84	80	95	Normal	F	37
Y5**	Y	Rear dump	0.02 (0.03)	93	94	99	Normal	F	27

5.8 Lung function test results coupled with symptoms in respiratory questionnaire

For workers with abnormal lung function test results showing moderate severity presented in Figures 5.14 – 5.20 with a summary of information obtained from the respiratory questionnaire in Figure 5.21.

The original completed respiratory symptoms questionnaire is provided as Appendix F and example of a completed questionnaire by an excavator saw operator provided as Appendix G.

Worker A3

Excavator + saw (Moderate obstruction)
FEV1 % of predicted 62
Maximum RCS individual exposure 0.32 mg/m^3
SEG MVUE RCS exposure 0.19 mg/m^3

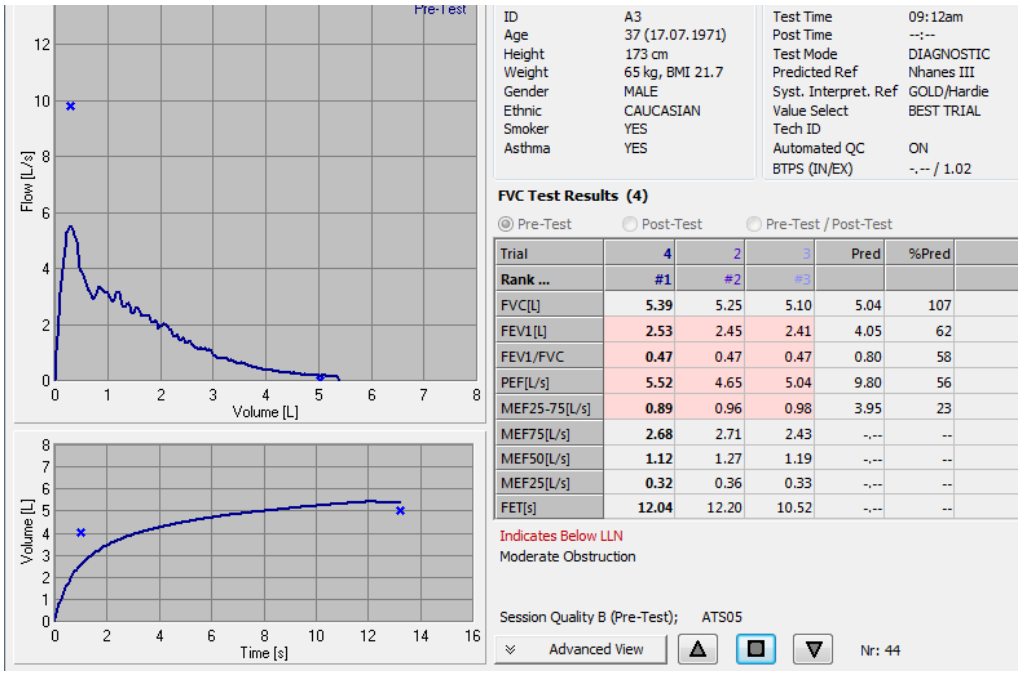


Figure 5.14 – Individual spirometry for a worker (A3) driving an excavator with saw showing moderate obstruction.

25 years in quarrying / stone mason industry smoker with asthma.
Symptoms reported by worker A3 included:

- Sleep broken by wheeze (5a).
- Wake up in the morning with wheeze (6a).
- Bring up phlegm from chest in morning in winter (12).
- Bring up phlegm on most days for as much as three months each year (14).
- In the past three years have had a period of (increased) cough and phlegm lasting for three weeks or more (15).

This operator drives the excavator and saw and doesn't normally wear a respirator inside or outside the excavator cabin. Wheezing is associated with asthma and excess mucus is associated with chronic bronchitis. As this operator is a smoker and the maximum exposure to RCS is 0.32 mg/m^3 this worker will be at much greater risk of being diagnosed with silicosis (HSE, 2002.)

Worker RS3.2

Excavator + saw (Moderate obstruction)
FEV1 % of predicted 65
Maximum RCS individual exposure 0.08 mg/m^3
SEG MVUE RCS exposure 0.19 mg/m^3

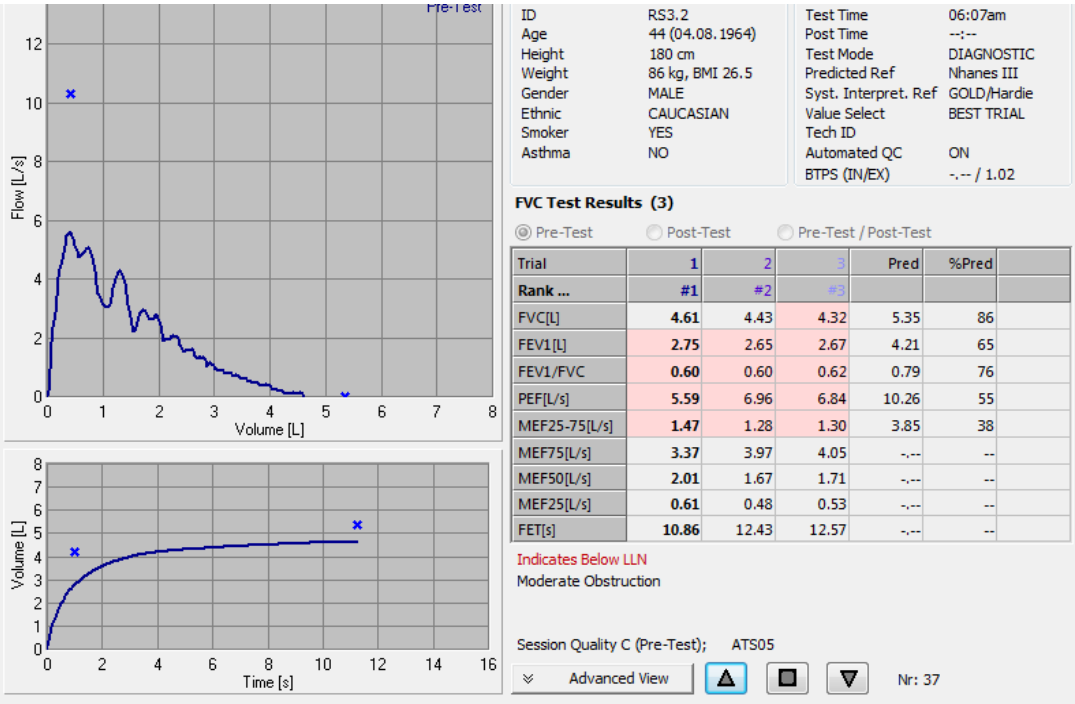


Figure 5.15 – Individual spirometry for a worker (RS3.2) driving an excavator with saw showing moderate obstruction.

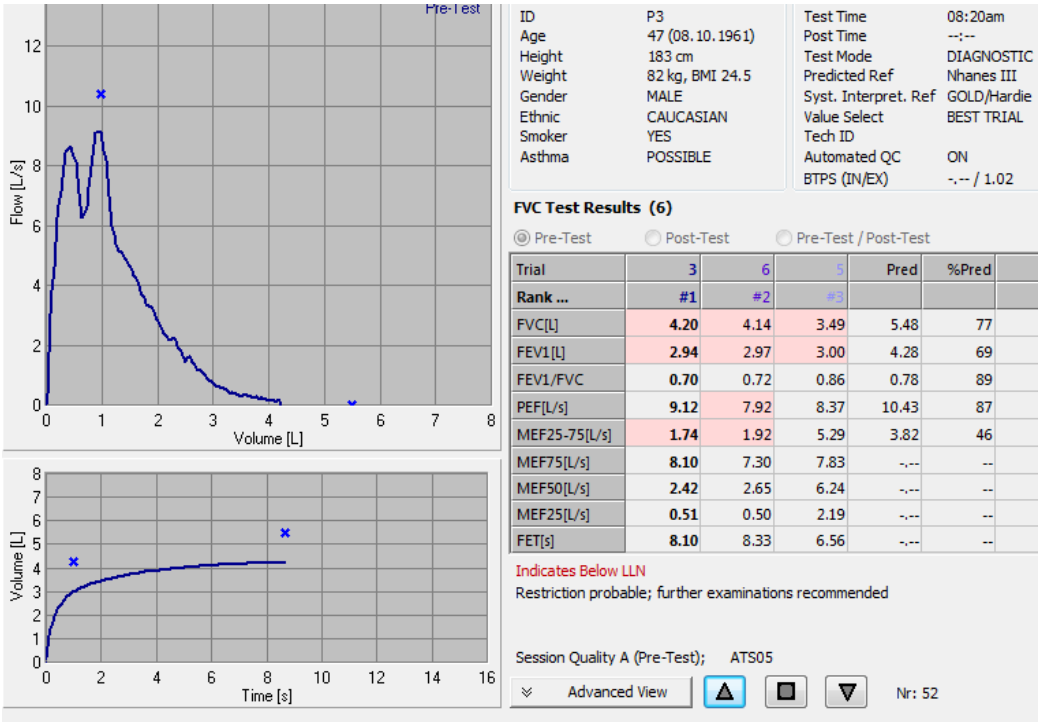
15 years in quarrying / sandstone. COPD reported. Symptoms reported by worker A3 included:

- Troubled by shortness of breath when hurrying on level ground or walking up slight hill. (1a).
- Wheeze run or climb stairs fast. (4a&4b).
- Wheeze if in a very dusty place. (7b).
- Symptoms are better at weekends and on holidays. (8a & 8b).
- Bring up phlegm during the day or night in winter (13).
- During the past three years have had chest illness that has kept from usual activities for as much as a week (17).

This operator drives the excavator and saw and doesn't normally wear a respirator inside or outside the excavator cabin. The COPD reported will be from the combined effects of both silica exposure and smoking. As symptoms are better when the worker is away from the operation this suggests that dust exposure is related to symptoms which may be reversible. This is confirmed where wheeze is noted if working in a dusty place. Breathlessness is strongly associated with emphysema.

Worker P3

Loader operator (Restriction probable – further examination recommended)
FEV1 % of predicted 69
Maximum RCS individual exposure 0.08 mg/m^3
SEG MVUE RCS exposure 0.04 mg/m^3



Trial	3	6	5	Pred	%Pred
Rank ...	#1	#2	#3		
FVC[L]	**4.20**	4.14	3.49	5.48	77
FEV1[L]	**2.94**	2.97	3.00	4.28	69
FEV1/FVC	**0.70**	0.72	0.86	0.78	89
PEF[L/s]	**9.12**	7.92	8.37	10.43	87
MEF25-75[L/s]	**1.74**	1.92	5.29	3.82	46
MEF75[L/s]	**8.10**	7.30	7.83	-.--	--
MEF50[L/s]	**2.42**	2.65	6.24	-.--	--
MEF25[L/s]	**0.51**	0.50	2.19	-.--	--
FET[s]	**8.10**	8.33	6.56	-.--	--

Figure 5.16 – Individual spirometry for a worker (P3) driving loader.

7 years in quarrying industry / reported that Doctor noted that there may be a spot on lung 6 – 8 months prior to completing this test and told by Doctor to cut down on smoking.
Symptoms reported by worker P3 included:

- Usually cough first thing in the morning during winter (9A).
- Bring up phlegm first thing in the morning during winter (12).

This operator drives the loader and doesn't normally wear a respirator inside the cabin. Chronic cough and phlegm are indicators of chronic bronchitis.

A restrictive disease pattern is indicative of silicosis.

Worker FV1

Loader operator (Restriction probable – further examination recommended)
FEV1 % of predicted 68
Maximum RCS individual exposure 0.06 mg/m^3
SEG MVUE RCS exposure 0.04 mg/m^3

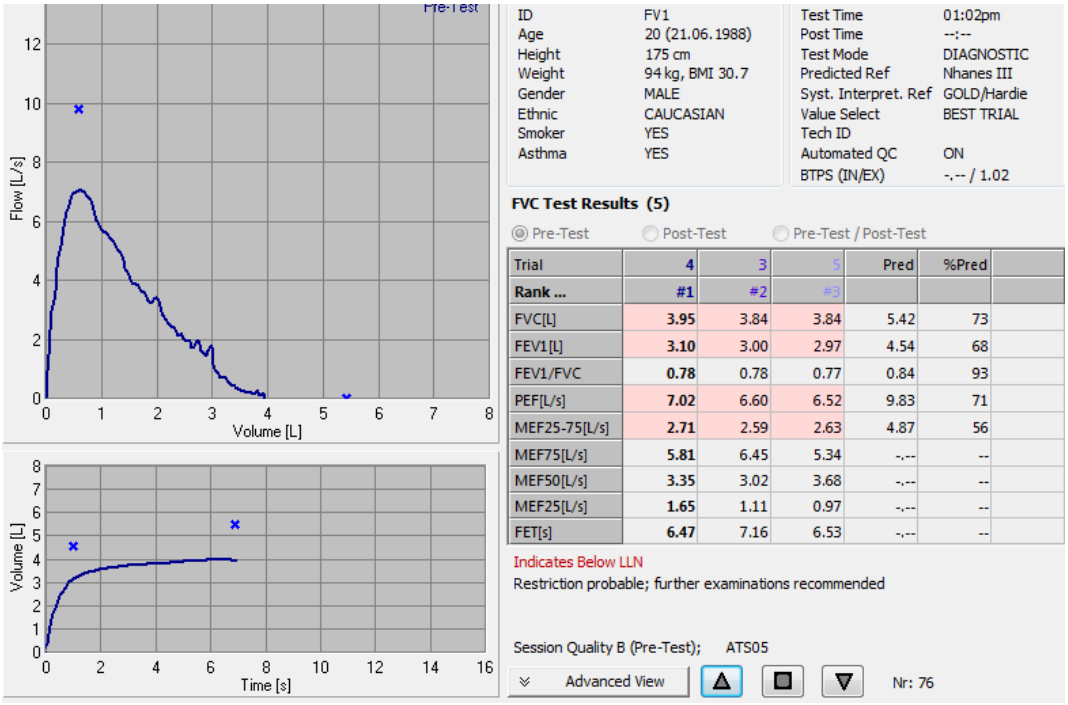


Figure 5.17 – Individual spirometry for a worker (FV1) driving loader.

2 years in quarrying industry
Symptoms reported by worker FV1 included:

- Cough & wheeze if run or climb stairs fast (4a&4b).
- Wake up in the morning with wheeze (6a).
- Wheeze in a smoky room (7).
- Usually cough first thing in the morning in winter (9)
- and during the day or night in winter (10).
- Cough on most days as much as three months a year (11).
- Usually bring up phlegm in the morning in winter (12)
- and during the day or at night in winter (13).
- Bring up phlegm like this on most days for at least three months a year (14)

This operator drives the loader and doesn't normally wear a respirator inside the cabin. Symptoms are consistent with asthma and chronic bronchitis. A restrictive disease pattern is indicative of silicosis.

Worker Y3

Loader operator (Severe obstruction)
FEV1 % of predicted 58
Maximum RCS individual exposure 0.02 mg/m^3
SEG MVUE RCS exposure 0.04 mg/m^3

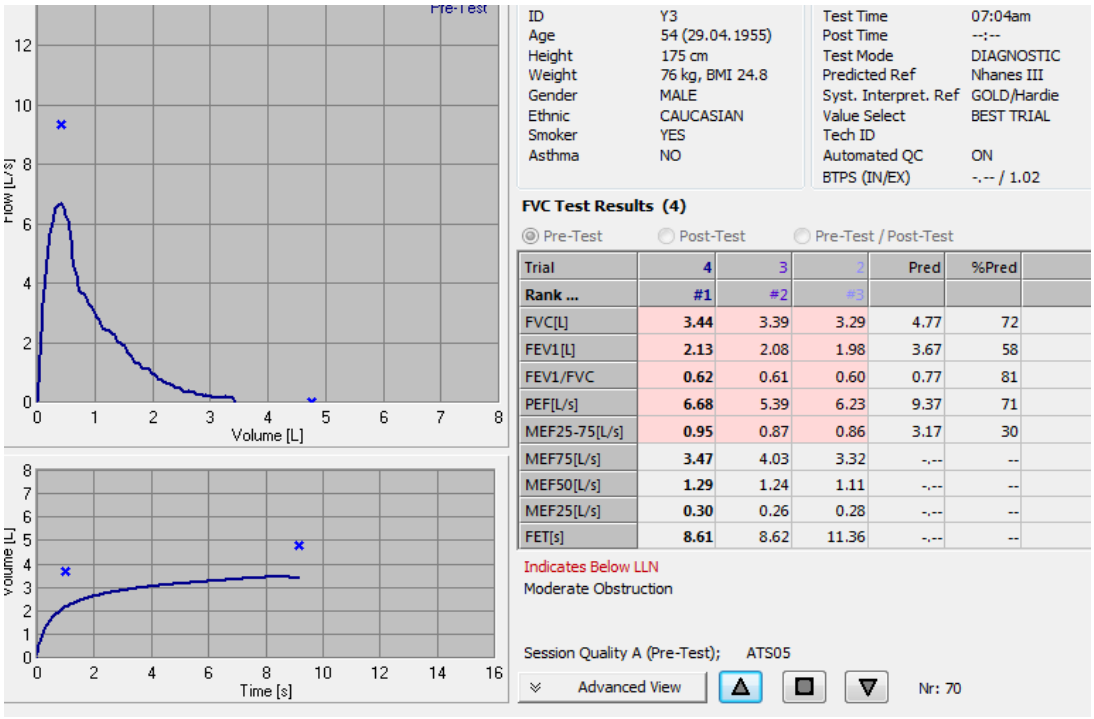


Figure 5.18– Individual spirometry for a worker (Y3) driving loader.

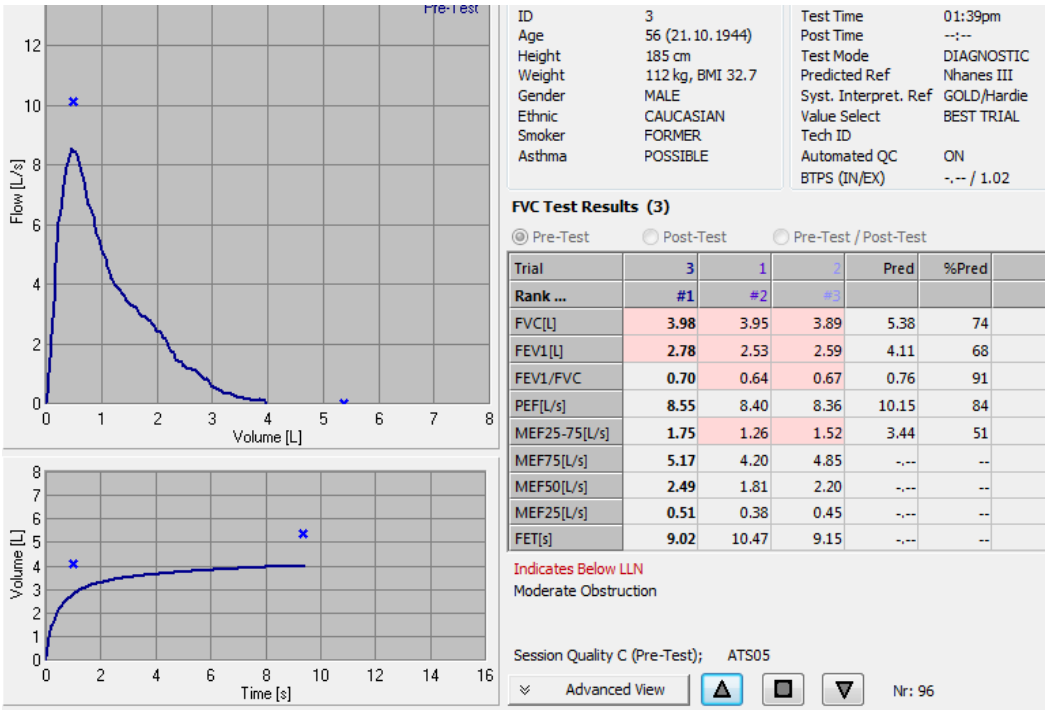
20 years in quarrying industry. Symptoms reported by worker Y3 included:

- Cough & wheeze (1, 4a & 4b).
- Troubled by shortness of breath, when hurrying on level ground or walking up slight hill.
- Get tight in the chest if run, or climb stairs fast (4c).
- Sleep is broken by wheeze and there is difficulty in breathing (5a & 5b).
- Wake in the morning with difficulty in breathing (6a&6b).
- Usually cough first thing in the morning, during day or at night in the winter (9&10).
- Cough on most days for as much as three months a year (11).
- In the past three years, have had a period of (increased) cough and phlegm lasting for three weeks or more & have had more than one such episode (16).

This operator has worked in the quarry industry for many years and is showing symptoms of chronic bronchitis and emphysema which will be exacerbated as this worker smokes.

Worker FD3

Loader / excavator / crusher operator (Moderate obstruction)
FEV1 % of predicted 68
Maximum RCS individual exposure 0.02 mg/m^3
SEG MVUE RCS exposure 0.05 mg/m^3



Trial	3	1	2	Pred	%Pred
Rank ...	#1	#2	#3		
FVC[L]	3.98	3.95	3.89	5.38	74
FEV1[L]	2.78	2.53	2.59	4.11	68
FEV1/FVC	0.70	0.64	0.67	0.76	91
PEF[L/s]	8.55	8.40	8.36	10.15	84
MEF25-75[L/s]	1.75	1.26	1.52	3.44	51
MEF75[L/s]	5.17	4.20	4.85	-.--	--
MEF50[L/s]	2.49	1.81	2.20	-.--	--
MEF25[L/s]	0.51	0.38	0.45	-.--	--
FET[s]	9.02	10.47	9.15	-.--	--

Figure 5.19 – Individual spirometry for a worker (FD3) loader/ excavator / crusher operator.

- Troubled by shortness of breath when hurrying on level ground or walking up slight hill. (1a).
- Cough & get tight in the chest if run or climb stairs fast (4a&4c).
- Usually bring up phlegm in the morning in winter (12)
- During the past three years have had chest illness that has kept from usual activities for as much as a week (17).
- Brought up more phlegm than usual in this illness (18).
- Have bronchitis & asthma (20).

This operator smokes unfiltered cigarettes. 30 cigarettes are consumed each weekday and 50 on weekend days. Worker symptoms indicate bronchitis (phlegm) asthma (wheeze) and emphysema (breathlessness).

Worker HW2

Dozer operator (Moderate obstruction)
FEV1 % of predicted 67
Maximum RCS individual exposure 0.05 mg/m^3
SEG MVUE RCS exposure 0.04 mg/m^3

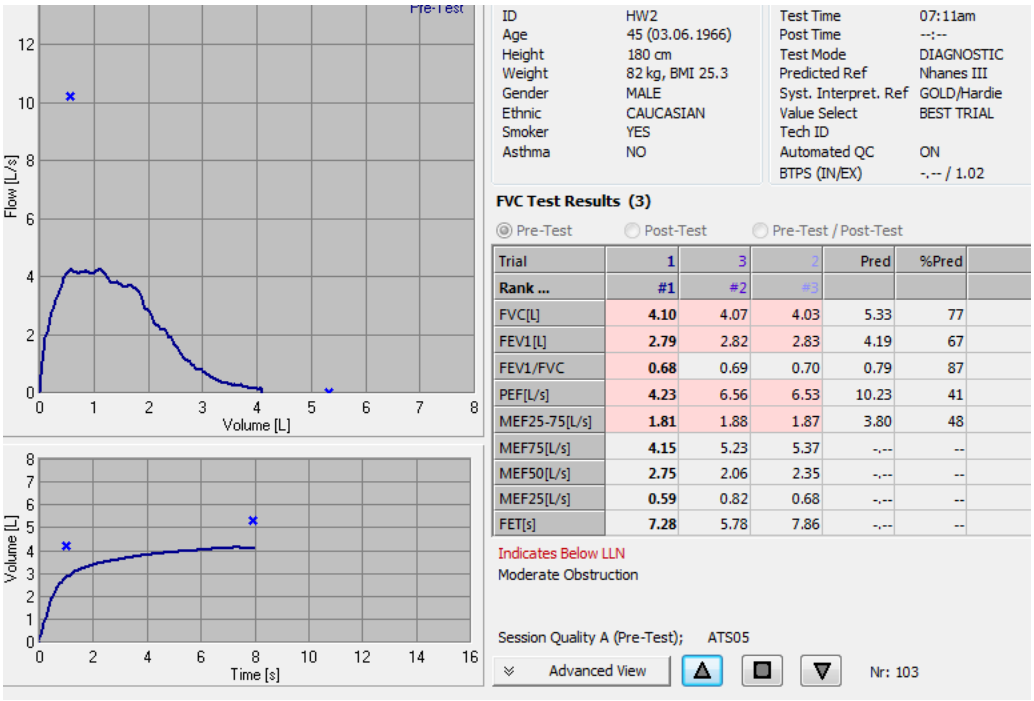


Figure 5.20 – Individual spirometry for a worker (HW2) Dozer operator.

1 year in quarrying industry and coal mining 5.5 years.
Symptoms reported by worker HW2 included:

- Troubled by shortness of breath when hurrying on level ground or walking up slight hill (1).

This operator has worked in the quarry for 5.5 years and is showing symptoms of emphysema which will be exasperated because this worker smokes.

5.9 Respiratory questionnaires.

The following Figure 5.21 shows where most respiratory question responses that were received.

Reported symptoms are as follows:

- Asthma (43%),
- Cough when running up or climbing stairs (37%),
- Bring up phlegm in the morning in winter (33%),
- Usually cough first thing in the morning in winter (33%), and
    - day or night in winter (30%);
- Breathlessness hurrying on level ground (27%) and,
    - wheeze when running or climbing stairs (27%).

Breathlessness, otherwise known as dyspnoea, can be graded along with FEV 1 % of predicted, as an indicator of chronic obstructive pulmonary disease (COPD). It can also be used to assess COPD severity. A correlation can be made between the MRC breathlessness (dysponea scale) and FEV1 % of predicted as described by Jones et al. 2012. The respiratory questionnaire can be used to screen for respiratory disease and is complimentary to spirometry. The St George's Respiratory Questionnaire (SGRQ), on the other hand, is typically used to evaluate the health-related quality of life (HRQL) for patients known to have respiratory disease whereas the MRC questionnaire is used as a tool to diagnose respiratory disease.

In this study the MRC respiratory questionnaire was used however for future reference a combination of both the MRC and SGRQ may assist to determine severity of lung disease along with FEV1 % of predicted.

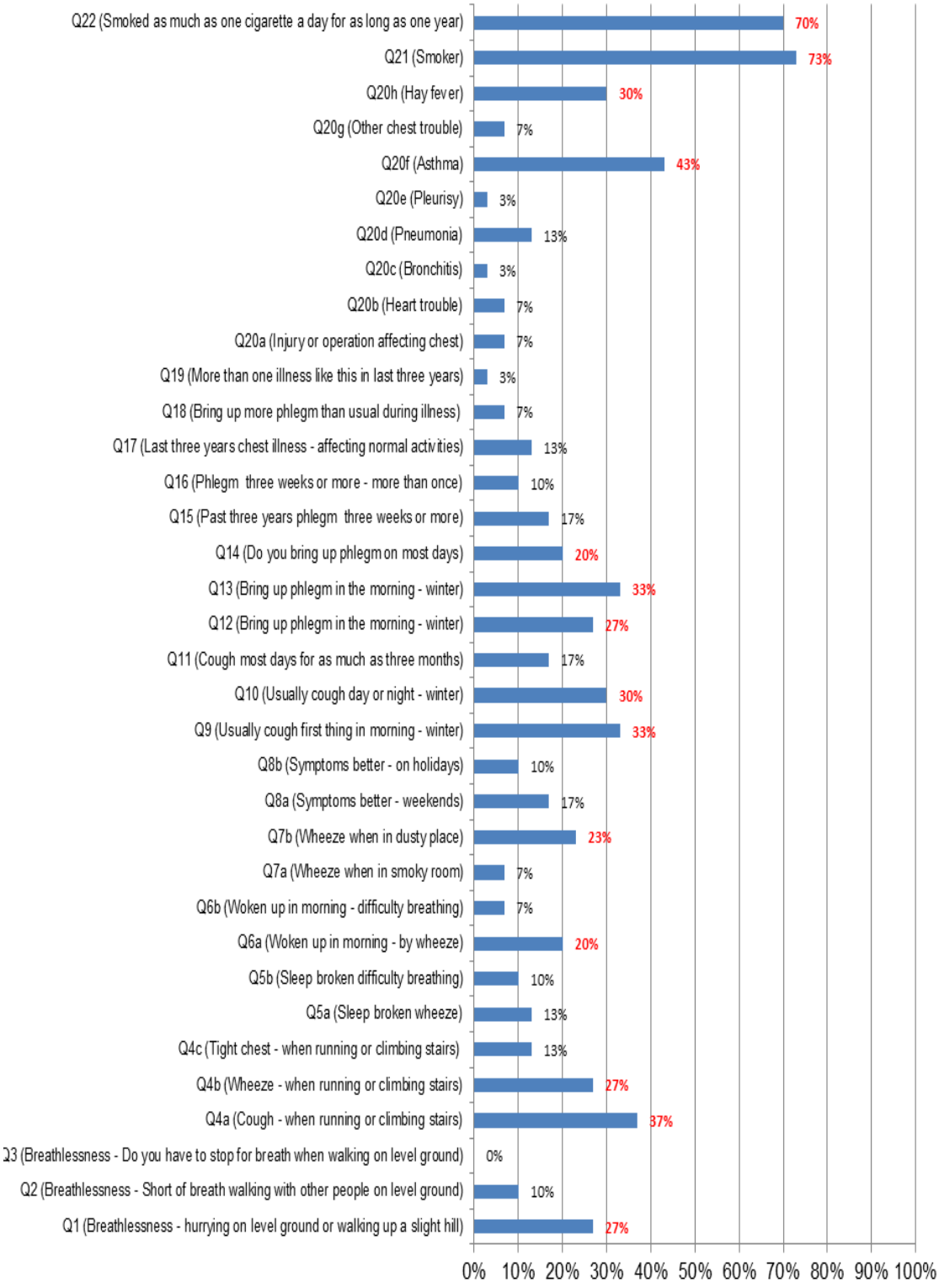


Figure 5.21 - % responses against each respiratory questionnaire question.

5.10 Discussion

The purpose of personal exposure monitoring was to evaluate exposure to RCS for both individuals and at a group (SEG) level. From sampling and analysis for RCS, five of the SEGs with a sample size of at least 6 were shown to be log-normally distributed. These data sets also had a geometric standard deviation of less than 3 (refer to Table 5.2). This is an indicator that the data is representative of a SEG and also further supports the correlation between RCS and loss of lung function as seen in Figure 5.5. In addition, the estimated average exposure for each SEG calculated as the MVUE was considered the best measure to compare with lung function as health effects are known to be related to dose. Dose is defined as being the amount of agent absorbed, taking into account the amount of RCS reaching the lungs, the deposition in the lung and duration of exposure (Edwards et al. 2013). Of the 47 workers monitored, 15 had at least one exposure that exceeded the SWA-ES. Based on the exposure assessment strategy employed, the British/Dutch, BOHS and NVva, (2011) and French Legifrance (2009) would find that these 15 workers are not in compliance with the SWA-ES as determined in the screening phase of the strategy. Of the remaining workers, based on the limited sample size it was not possible to demonstrate compliance or non-compliance. For example, if the average exposure is approximately 50% of the SWA-ES, with a geometric standard deviation of about 2, such as that obtained for the excavator operator, 21 samples will be required for this SEG alone to be 95% confident that the true mean exposure (MVUE) is less than the SWA-ES (Ignacio & Bullock 2006). Another measure to demonstrate compliance is the upper tolerance limit (UTL) which is the 95^{th} percentile with a 95 % upper confidence limit (Ogden & Lavoue 2011). Upper tolerance limits ($UTL_{95,95}$) are not shown. These metrics can be used as a measure of compliance for individual workers, or where exposure is to acute health hazards. Many more samples would have been required to estimate the 95^{th} percentile with 95% confidence. For example where the result is two thirds of the SWA-ES, close to that for the service operator, and the geometric standard deviation is about 3; approximately 150

measurements will be required for this SEG (Ogden & Lavoue 2011). To be able to statistically demonstrate compliance with reasonable power and traditional confidence limits usually requires impracticable numbers of samples, especially when the true 95 percentile is about 20% to 30% of the OEL (Ogden & Lavoue 2011, p. D64). As it has been determined that the estimated average is the best measure of exposure, statistical analysis was carried out using a combination of Ndexp® a tool developed by Jerome Levoue (nd), in conjunction with IHSTAT. Using Ndexp® allowed a best-estimate for treating results < LoQ and replaced these values with computer generated values by imputation. This enhanced statistical analysis resulting in a more accurate determination of the profile distribution and estimated average using IHSTAT®. Statistical analysis confirmed a loss of lung function at exposures at, or close to the current SWA-ES. This study shows the importance of the use of lung function measurement (spirometry) along with RCS personal exposure monitoring to identify where control measures are most needed. Results from this assessment should raise awareness and provide the impetus in the prevention of progression of lung disease resulting from exposure. Of the workers tested for lung function, those with moderate lung function loss, shown in Table 5.10 included 5 workers with obstructive and 2 with restrictive lung function patterns being indicators for COPD and silicosis respectively. A significant correlation between forced expiratory volume in one second as a percentage of predicted (FEV1 % of predicted) and FEV1/FVC as a percentage of predicted and RCS exposure (Figures 5.3 & 5.4) has been demonstrated ($p<0.05$). There was a downward trend in lung function performance in relation to higher RCS exposures. This data can only be interpreted collectively as a trend has only been established across all of the SEGs for groups and not individuals. For statistical analysis and comparison of lung function measurement: FEV1 is noted by John's & Pierce (2007), as a sensitive measure of lung performance & Pellegrino et al. (2005) grades severity on FEV1% of predicted. Therefore, for further statistical analysis by ANOVA, the focus is on FEV1 % of predicted with RCS exposures. FEV1 % of predicted is

more sensitive for lung function measurement to indicate abnormal lung function as compared with other parameters as seen in Tables 5.3 & 5.12. When using FEV1% of predicted there were more results (9/44) indicating abnormal lung function HSE (2016) compared with FVC % of predicted (6/44) or FEV/FVC % of predicted (1/44). When the data were re-analysed (Figure 5.3) using SEGs with at least 6 samples and at least 2 workers in the SEG there was an even stronger correlation between exposure and loss of lung function. Analysis of variance (ANOVA) demonstrated a level of variance that is not significantly different between SEGs for FEV1 % of predicted. Albeit, ANOVA carried out between the crusher and excavators FEV1 % of predicted, demonstrated that the difference between these similar exposure groups (SEGs) approached significance ($p = 0.069$). Further analysis by ANOVA confirmed that there was a significant difference when similar exposure groups were banded into three groups A, B and C as shown in Table 5.6. This was carried out to increase the sample number for ANOVA and increase statistical power. Table 5.6 shows how the similar exposure groups have been grouped into A, B, C. ANOVA carried out comparing groups A, B and C demonstrated a significant difference between groups for RCS exposure ($p < 0.05$) and FEV1 % of predicted ($p < 0.05$) as shown in Tables 5.7 and 5.8. A t-Test (Table 5.9) further confirmed that there is a significant difference between groups A and C. It was also shown that more smokers had obstructive disease lung patterns as compared to non-smokers. This has been shown in Figures 5.12 & 5.13 where workers exposed to RCS ≥ 0.04 mg/m^3 where lung function symptoms between smokers and non-smokers were compared. Of the workers with loss of lung function loss (of moderate severity) determined from FEV1 % of predicted (Table 5.12), these same workers also reported symptoms consistent of obstructive lung disease as shown in Table 5.13. For the same group of workers with a lung function score showing moderate severity, there is a correlation between years in the industry with loss of lung function measured as FEV1 % of predicted of a normal population as shown in Figure 5.22. The results from this study

indicate that there is an increased risk from loss of lung function with respirable dust & RCS exposure, smoking & years in the industry all contributing to poor lung health. Further discussion is provided in Chapter 7.

Table 5.13 Comparison of FEV1 % of predicted (of moderate severity) with years in quarrying / dimension stone mine with respiratory symptoms.

Code	FEV1 % of predicted	Years	Smoker	Asthma	Wheeze	Breath-lessness	Cough	Phlegm	Pattern
A3	62	25	√	√	√		√	√	Obstruction
RS3.2	65	15	√		√	√		√	Obstruction
P3	69	7	√	√			√	√	Restriction
FV1	68	2	√	√	√		√	√	Restriction
Y3	58	20	√		√	√	√	√	Obstruction
FD3	68	6	√	√		√	√	√	Obstruction
HW2	67	5.5	√			√			Obstruction

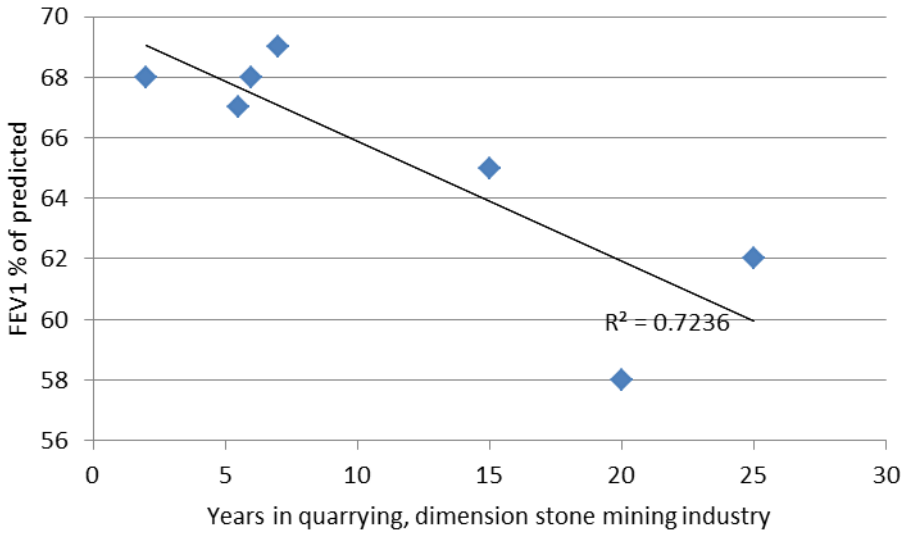


Figure 5.22 Comparison of lung function loss measured as FEV1 % of predicted showing moderate severity with years in industry.

Chapter 6 Particle size, shape & composition as determined by electron microscopy

6.1 Introduction

Chapter 5 explored the risk of exposure to RCS in a range of SEG's across nine sites including quarries and dimension stone mines in Queensland, Australia. This study demonstrated that the lung health of workers is being affected, showing a correlation between dust exposure, reduced lung function, and reported respiratory symptoms. Chapter 6 reports electron microscopy findings to evaluate particle size distribution, and shape, to identify physical characteristics responsible for these particles being entrained in breathing air, and reaching the lung resulting in adverse lung health. As discussed, EAD is important because: this is the particle size measure unit which sets the design criteria for the cyclone personal sampling head as per AS-2985-2009 (Standards Australia 2009). It is postulated that the use of EAD is an overly simplified term in the context of the Australian Standard. Uncertainty associated with EAD must be explicit, which is further explained in this chapter. To capture the physical characteristics of RCS responsible for adverse lung health, further analysis of selected RCS samples already quantified by infrared-spectroscopy were subsequently analysed by electron microscopy (EM). This EM analysis provided a more detailed understanding of particle size and shape. By comparing particle size distributions from selected real workplace samples with the theoretical sampling efficiency curve presented in Standards Australia (2009) AS-2985-2009 a clearer picture about particle deposition in the lung has evolved.

6.2 Particle size analysis methodology

A requirement in sample selection is that the particulate matter on filters should have mass to provide sufficient quantity of particles to allow for representative size distribution analysis. The selection of samples for the detailed analysis was focussed on mass, which means that not all samples and therefore the cohort of

workers were not further analysed. Selected samples for EM analysis are shown in Table 6.1. A second consideration, was to further understand the impact of the air cleaning RESPA® technology effectiveness on an excavator saw cabin on reducing the operator's exposure to $PM_{2.5}$, high risk respirable dust (median diameter of 2.5 μm), and PM_1 (Particulate matter less than 1 μm in diameter) (Hedges et al. 2010). Samples selected for subsequent EM analysis (shown in Table 6.1) were provided to Microanalysis Australia. A representative sub-sample was cut from the filter membrane of about 6 mm by 6 mm in size. The sub-sample was then placed on top of a double sided carbon tab before being carbon-coated. The non-conducting samples require a coating prior to SEM analysis to prevent charging whilst being analysed by the electron beam. The samples were analysed using a JEOL 5800LV scanning electron microscope (SEM) fitted with an Oxford INCA energy dispersive spectrometer (EDS). Energy dispersive spectrometry (EDS) is a semi-quantitative technique ideally carried out on optically flat samples. Therefore, factors such as sample unevenness may bias elemental concentration. EDS has a resolution of about 5 μm. Microanalysis state that particles less than 5 μm may contain elemental concentrations influenced by their surroundings. Images of the filters were obtained using backscatter electrons. Image brightness is proportional to average atomic number, the brighter the pixel the higher the atomic number of the element. Images were taken of the sub-sample and then particles were analysed for their elemental composition and size. Where particles are not close to being spherical, the largest diameter is reported. Particle counts are carried out for each sample and collectively across all samples. From these counts, particle size distributions are determined. IHSTAT® a specially designed excel® workbook for occupational hygiene statistical analysis, was used to calculate median diameters and distribution of best fit (i.e. log-normality). To determine whether there is a relationship between median physical diameter and percentage of RCS in each sample, a scattergram graph is produced using excel®. The cumulative sampling efficiency curve is produced for particles where silicon and oxygen are major elements. This indicates that these particles

are free silica. Size estimates for this curve are based on physical diameters. This curve is compared with the theoretical curve based on EAD provided in AS 2985-2009 (Standards Australia 2009) using excel®.

6.3 Results

6.3.1 Particle size analysis

Table 6.1 shows which samples were selected for Electron Microscopy analysis, along with the concentrations of respirable dust and respirable crystalline silica, % of respirable crystalline silica in respirable dust and physical median diameters for each sample. To determine the median physical diameter in the respirable dust samples, a particle size is count was conducted which is summarised in Table 6.2.

Table 6.1: Selected filter samples for analysis by electron microscopy.

Filter Id	Worker code	Site Code	Condition	SEG Operator / location	Respirable dust mg/m^3	RCS IR mg/m^3	% RCS	Physical Median diameter (µm)
F6439	FV2	F	None	Crusher	0.50	0.07	14	4.1*
F5723	Y	Y	None	Crusher	1.40	0.25	18	5.7***
F5137	P3	P	None	Loader	0.27	0.05	19	4.4*
F5007	P2	P	None	Loader / crusher	1.30	0.35	28	4.3*
F5131	P5	P	None	Service	0.41	0.07	17	3.1
F6727	R2	R	None	Excavator + saw	0.42	0.12	29	3.6
F4999	A3	A	None	Excavator + saw	1.10	0.32	28	2.9*
F6725	Fixed	R	None	Excavator + saw (in cabin)	0.50	0.11	22	3.6**
F6348	R2	R	RESPA®	Excavator + saw	0.27	0.04	15	4.0**
F5225	R2	R	RESPA® Recirc	Excavator + saw	0.27	0.11	41	3.2**
F5243	Fixed	R	RESPA® Recirc	Excavator + saw (in cabin)	0.08	0.03	38	2.3*

Notes: * log-normal distribution, ** log-normal & normal distribution, *** normal distribution, Recirc – second RESPA® unit installed to filter and clean re-circulated air, SEG Similar Exposure Group

Table 6.2 shows both the geometric mean and median diameter, for all particle counts, being close to the theoretical median in accordance with AS2985-2009,

which is the Australian Standard for sampling respirable dust (Standards Australia 2009).

Table 6.2: Summary of particle size analysis for all filters.

Number of counts	**165**
Number of filter samples	**11**
Maximum diameter (µm)	22
Minimum diameter (µm)	0.6
Geometric mean (µm)	3.8
Geometric standard deviation	1.8
Median (µm)	3.9

The collective size distribution for both particles and silica across all samples in Table 6.1 are seen in Table 6.2 & Figures 6.1 & 6.2 respectively. The particle size distributions are log-normal. Figure 6.1 show results of particle size distribution across all individual samples which are all log-normally distributed. The demonstration of log-normality suggests that the sample size breakdown represents exposure and indicates that the number of counts is sufficient to determine particle size distribution.

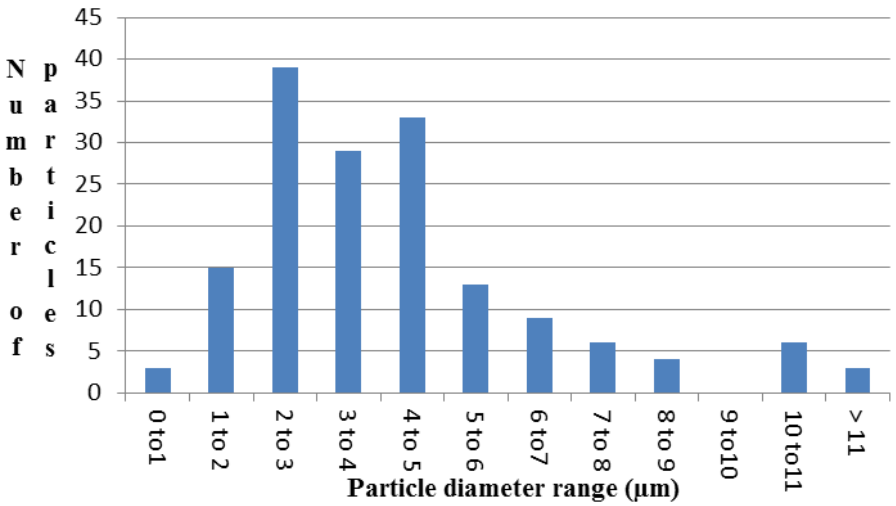


Figure 6.1 – Distribution of physical particle diameters across EM samples for all particle counts.

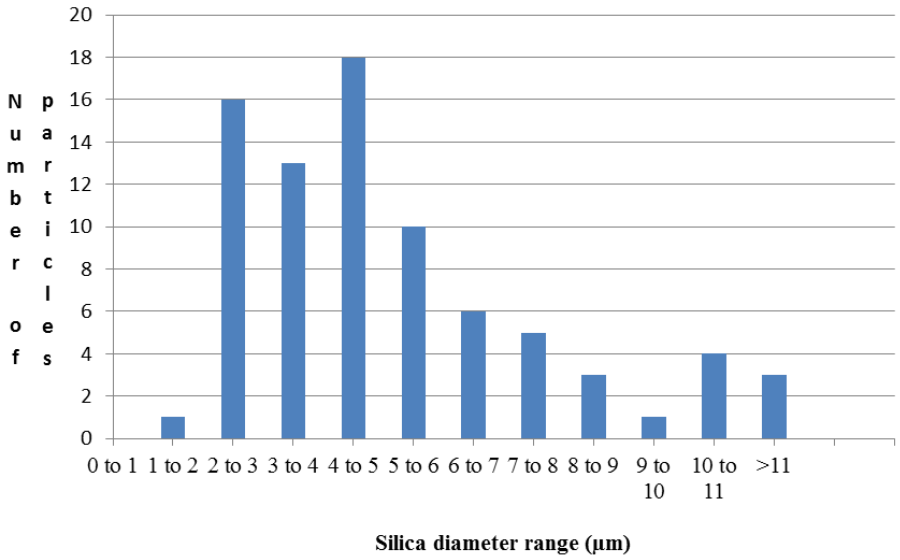


Figure 6.2 – Distribution of physical particle diameters across all EM samples for where major elements are silicon and oxygen indicating that particles are free silica.

To demonstrate where the greatest differences are against theoretical AS2985-2009 (Standards Australia) for each particle size, comparisons have been made between actual and theoretical as shown in Figure 6.3. There is a strikingly good match even though neither particle density nor shape has been factored into the diameter to equate diameter to EAD.

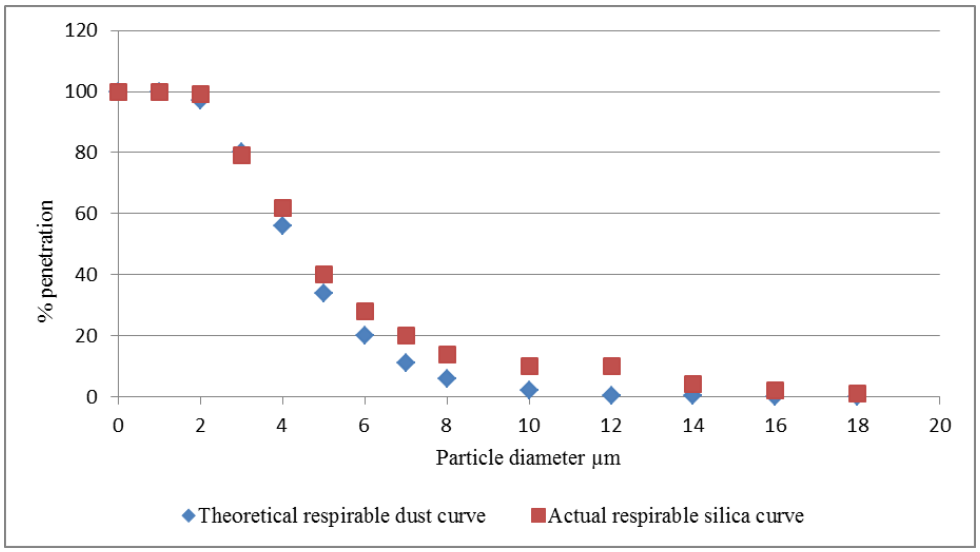


Figure 6.3 Graphical representation of theoretical AS 2985 – 2009 (Standards Australia 2009) **sampling curve, with actual field data for silica particles across all EM samples. The theoretical curve is EAD (median diameter 4.25 µm) whereas the actual curve is for physical diameter (median diameter 4.4 µm).**

It was expected that the curve showing particle physical measurements would have had more cumulative plot points much lower than shown as the density of quartz is 2.65. To quantify the difference at each particle size, percentage differences between theoretical EAD and actual physical diameters are shown in Table 6.3.

Table 6.3 Theoretical cumulative data as per AS2985-2009 (Standards Australia 2009) **and the calculated real data from this study.**

Diameter µm	Cumulative theoretical % Based on EAD, AS2985 (Standards Australia 2009)	Actual Cumulative data % Based on physical diameter of silica particles	Difference
0	100	100	0
1	100	100	0
2	97	99	2
3	80	79	-1
4	56	62	6
5	34	40	6
6	20	28	8
7	11	20	9
8	6	14	8
10	2	10	8
12	0.5	10	9.5
14	0.2	4	3.8
16	0.1	2	1.9
18	0	1	1

There was a larger difference for particles between 4 µm and 12 µm which was unexpected. This is demonstrated in Table 6.3 and Figure 6.2. The median physical diameter for silica particles is 4.4 µm and equates to an approximate EAD of 7.2 µm (for a spherical particle), which is much larger than what would be expected from AS 2985 – 2009 (Standards Australia 2009), having a theoretical 50% cut point or assigned median EAD of 4.25 µm.

This indicates that for particles, especially those between 4 and 12 µm, there may be an over-riding factor which dominates respirability. To understand if there is a difference in median diameters for all particles counted in relation to % RCS in respirable dust, median silica diameters are plotted against each corresponding % RCS. This can be seen in Figure 6.4.

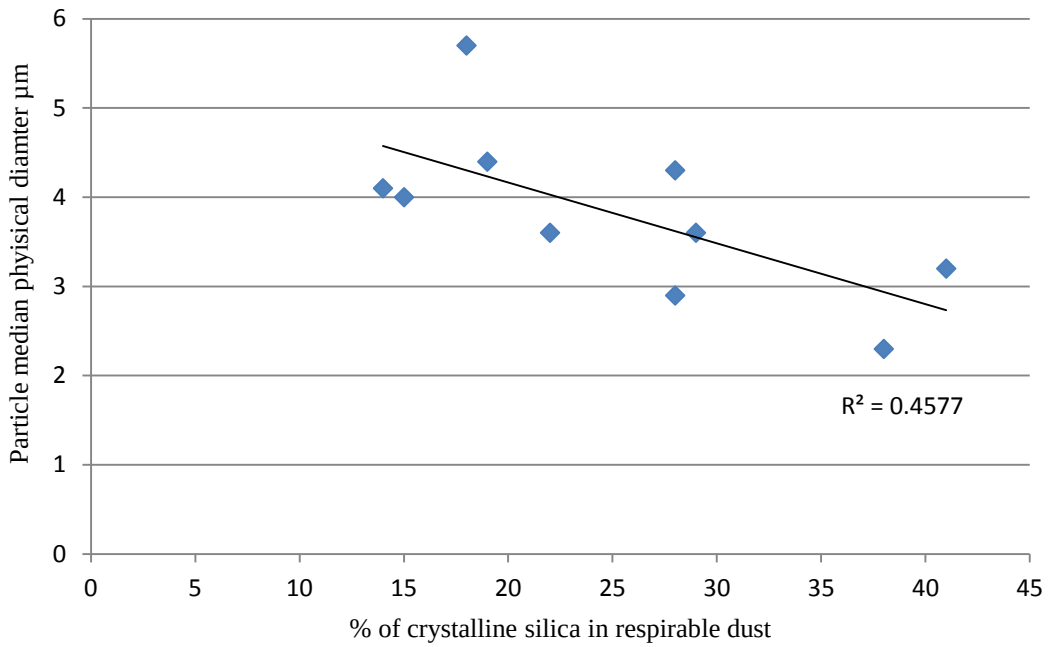


Figure 6.4: Median diameters of particles for each sample compared with % of crystalline silica in respirable dust.

The trend indicated in Figure 6.4, suggests that as the % of respirable crystalline in respirable dust increases, then there is a reduction in median diameter. This demonstrates that the finer the respirable dust particles then the greater proportion of the finer particles which are crystalline silica. This is important and demonstrates that there may be a greater non-linear risk as the % of RCS increases because RCS particles become smaller. This has implications for the setting of RCS exposure standard. In Chapter 4, samples were taken inside an excavator & saw cabin after an air cleaning RESPA® unit was installed (refer to Chapter 4 for a full description). When a sample is taken inside the cabin when a second recirculation air cleaner RESPA® unit is installed, there is a change in particle size distribution compared to the air being sampled without a RESPA® unit. When the RESPA® is installed, there is a marked reduction in the median

physical diameter of particles with the distribution being skewed more towards smaller particles as seen in Figure 6.5.

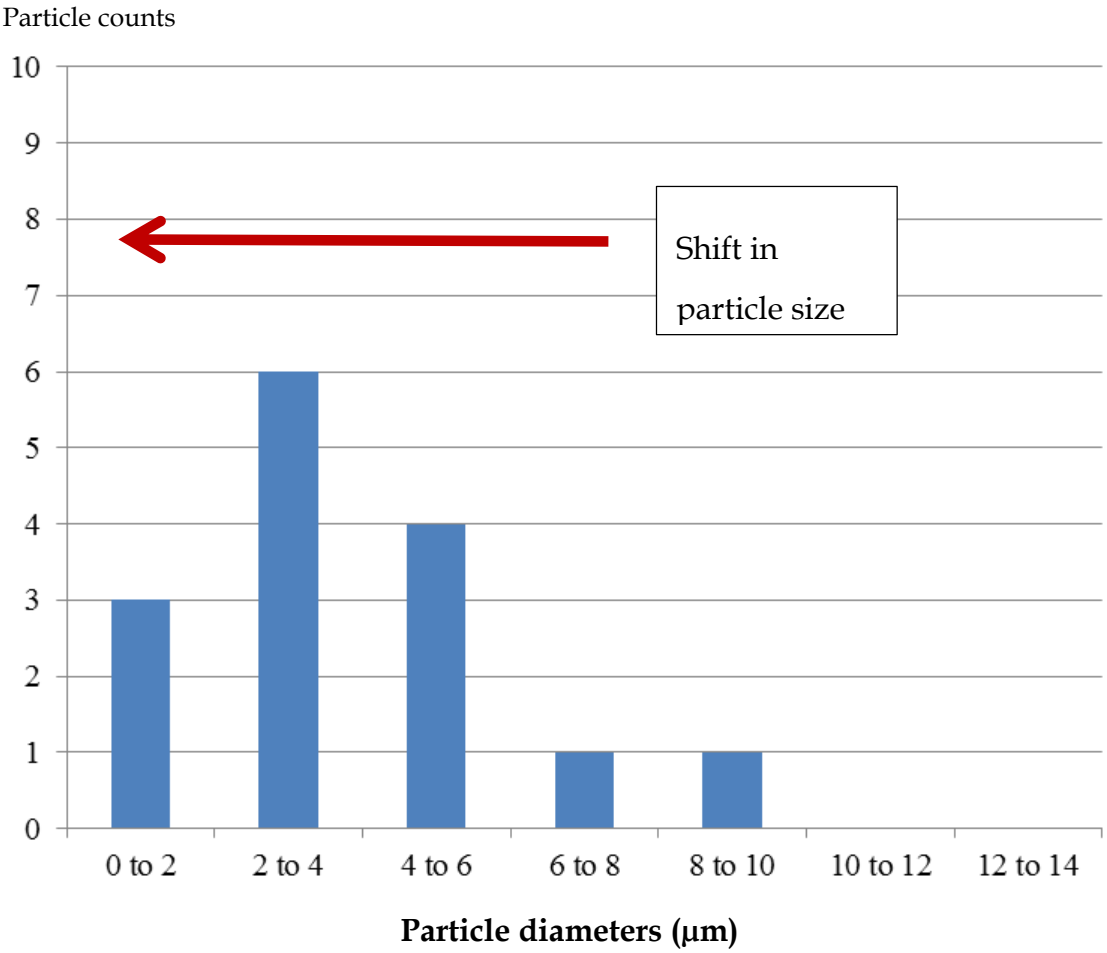


Figure 6.5: Physical diameter particle size distribution curve for the sample taken inside an excavator cabin with primary RESPA® and secondary RESPA® units installed.

The second RESPA® unit installed to clean recirculated air may be size-selectively removing larger particles, and concentrating the smaller silica particles. This observation is important and simply relying on measuring particulate matter inside the cabin as a measure of effectiveness is not a good measure of effectiveness for filtration of the smallest and most pathologically dangerous RCS particles. This is also consistent with an observation, made in Chapter 4, showing that there is greater reduction for particulate matter (PM)

(Figures 4.3 & 4.5) when compared to RCS, by direct RCS measurement, before and after installation of a RESPA® unit. Relying on measurement of PM is inferior to the direct measurement of RCS as a determinant of filtration efficiency.

6.3.2 Morphology.

To get a better understanding of particle morphology, all micrographs of the dust samples identified in Table 6.1 were examined, and provided in Appendix I. Samples with interesting morphology are highlighted in Table 6.4. Many of the samples have particles that are elongated and for two samples F6439 and F6727 the morphology for some of the particles are fibrous and needle-like respectively.

Table 6.4 Selected micrographs showing the variation in morphology.

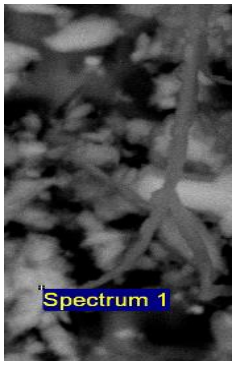
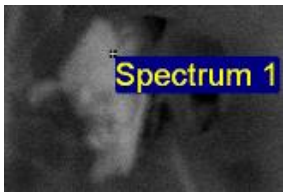
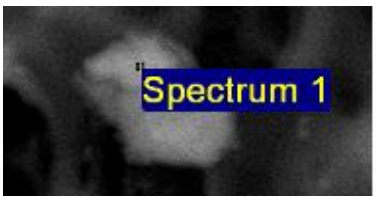
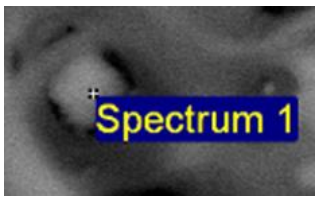
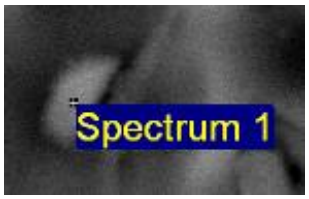
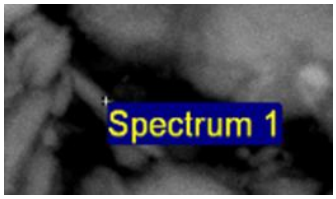
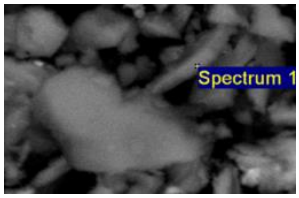
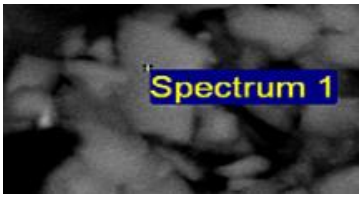
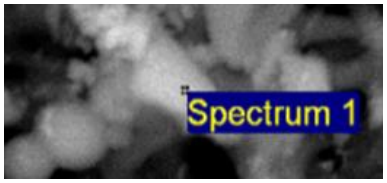
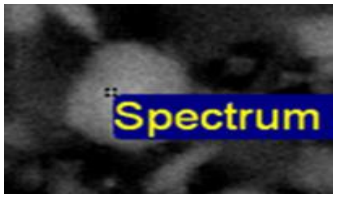
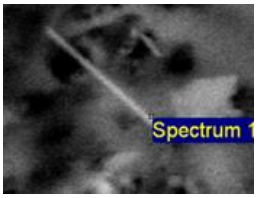
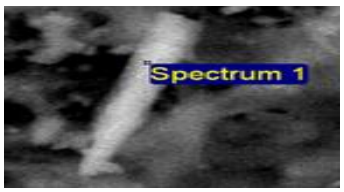
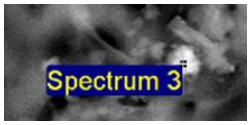
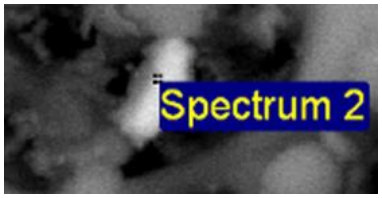
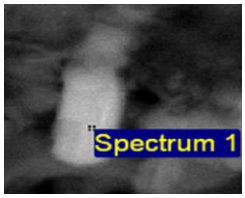
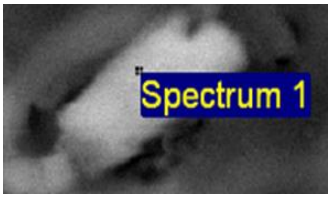
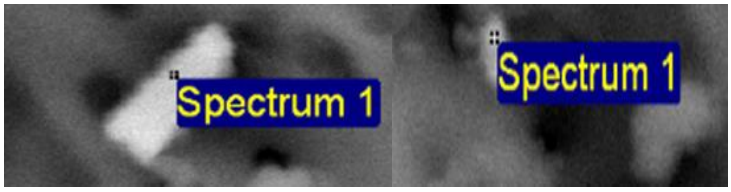
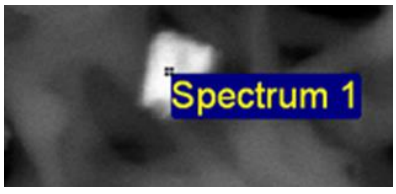
Filter Id	Worker Code	Site Code	Dust generation activities	Selected micrographs and comments
F6439	FV2	F	Crushing	  Many of the particles had oblong geometry as shown in spectrum 2 and one of the sites of interest had minerals with fibrous morphology shown in spectrum 1. Preliminary investigation in the particle in spectrum 1 indicates that this is a fibrous mineral silica – erionite.
F5723	Y	Y	Crushing	  Many of the particles had oblong geometry as shown above
F5137	P3	P	Vehicular movement / loading	 .  Particles had mixed morphology between oblong, rectangular and close to square and angular geometry
F5007	P2	P	Vehicular movement / loading crushing	 .    Many of the particles have rod like morphology
F5131	P5	P	General	  Mixed morphology.

Table 6.4 Selected micrographs showing the variation in morphology (cont).

Filter Id	Worker code	Site Code	Dust generation activities	Selected micrographs and comments
F6727	R2	R	Sawing rock / vehicular movement	   Combination of mixed morphology with some needle like particles observed.
F4999	A3	A	As above	  Combination of mixed morphology with some needle like particles observed.
F6725	Fixed position	R	As above	  Combination of mixed particle shapes with oblong / rectangular fragments.
F6348	R2	R	As above	 .  Combination of mixed particle shapes with oblong / rectangular fragments
F5225	R2	R	As above	 Combination of mixed particle shapes with oblong / rectangular fragments.
F5243	Fixed position	R	As above	 Combination of mixed particle shapes with oblong / rectangular fragments

The particle seen in Figure 6.6 is from a personal sample taken for a loader operator working in a sand, soil and gravel quarry. Major elements are silicon and oxygen denoting free silica (RCS). The physical diameter of this particle is 2.2 µm which equates an EAD of 3.6 µm (applying the following formula: $dpa = dps\sqrt{Pp}.$, Density of quartz = 2.65). As this particle is spherical and the spectrum indicates that it is pure quartz the true aerodynamic diameter can be confidently calculated.

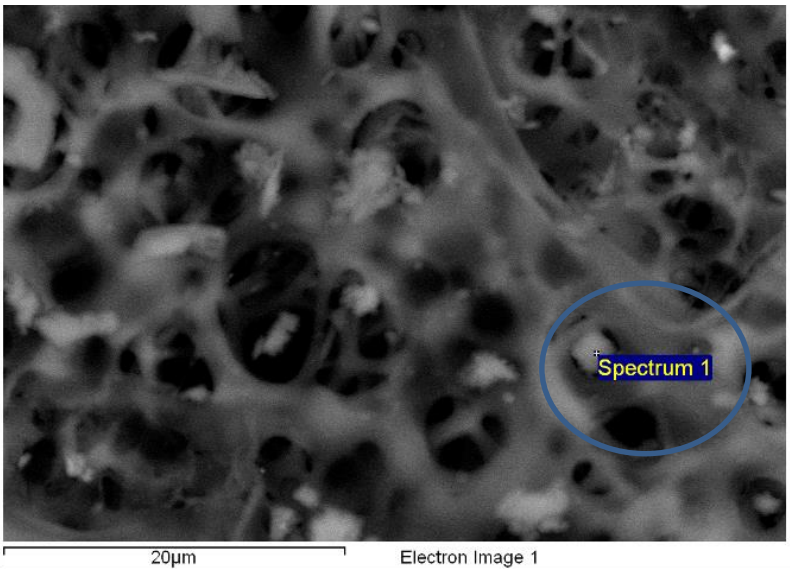


Figure 6.6: F5137 particle 1 micrograph.

The elemental spectrum for the micrograph (Figure 6.6) in Figure 6.7 notes major elements being silicon and oxygen (free silica). The aluminium will be from clay contamination, chlorine from the polyvinyl chloride (PVC) filter and carbon from the filter coating for EM analysis.

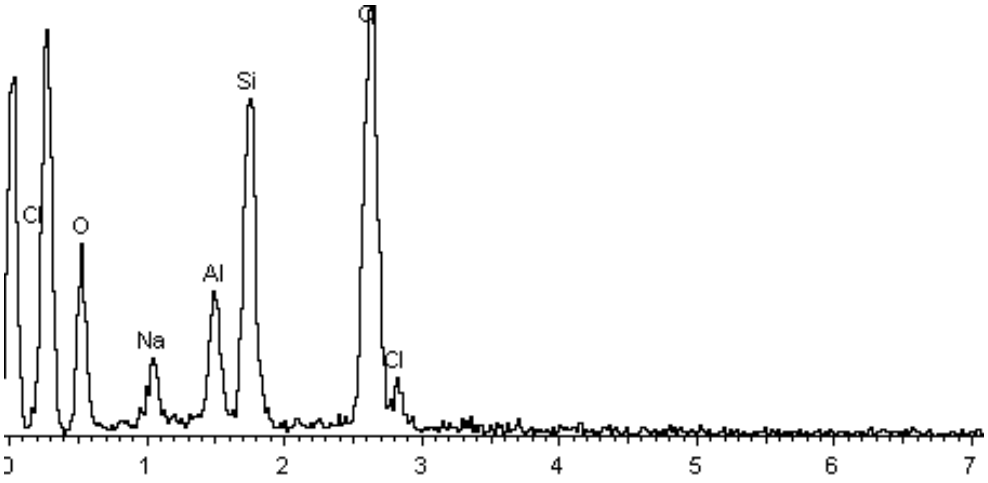


Figure 6.7: F5137 particle 1 elemental spectrum.

The particle seen in Figure 6.8 is from a personal sample taken for a loader/ crusher operator in the same sand soil and gravel quarry as the previous sample. Even though the physical length of this particle is about 8.5 µm the width varies from <1 µm to about 5 µm.

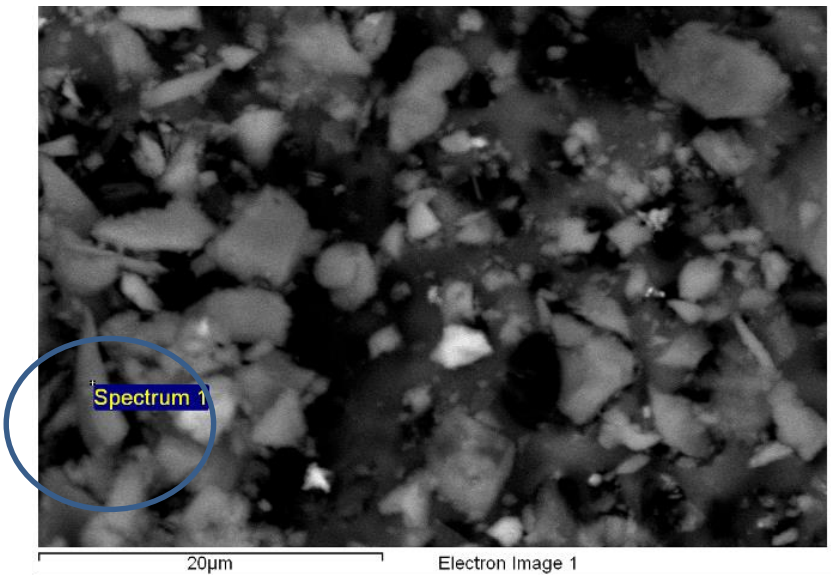


Figure 6.8: F5007 particle 6 micrograph.

The elemental spectrum for the micrograph (Figure 6.8) in Figure 6.9 notes major elements being silicon and oxygen (free silica).

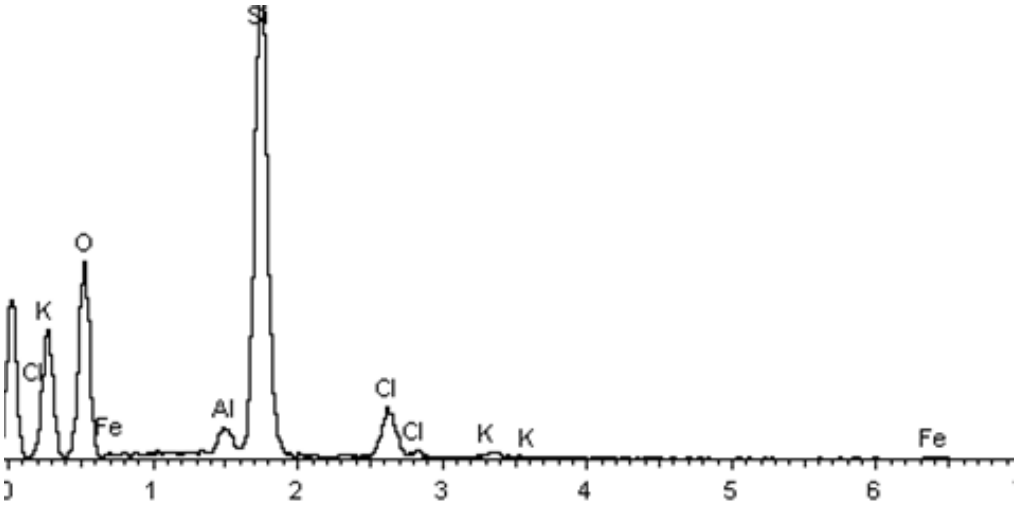


Figure 6.9: F5007 particle 6 elemental spectrum.

The particle seen in Figure 6.10 is from a personal sample taken for an excavator with a circular saw attachment cutting through sandstone in a dimension stone mine. The physical length of this particle is 12.2 µm with a width < 3 µm which means that this particle is classified as a respirable fibre.

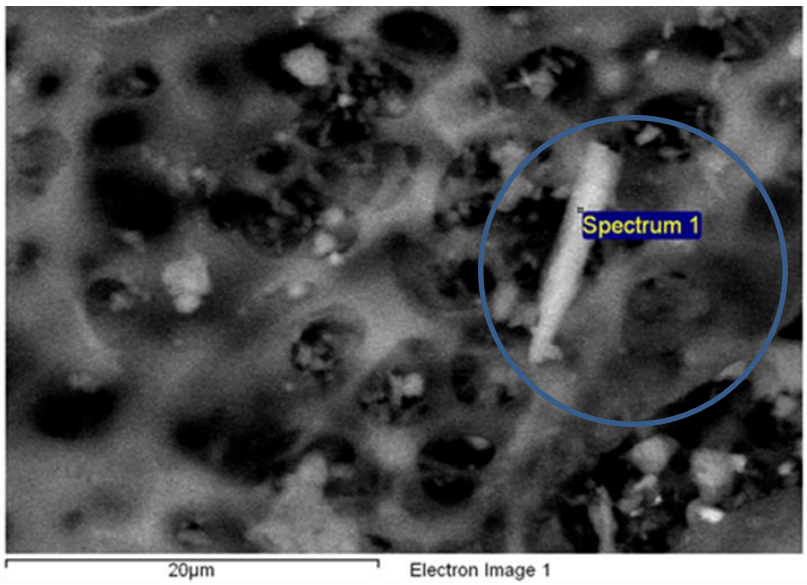


Figure 6.10: F6727 particle 3 micrograph.

Although the major elements from the micrograph (Figure 6.10) in Figure 6.11, are identified as silicon and oxygen indicating free silica, other elements have been identified albeit in minor quantities including calcium, magnesium and iron which need further investigation.

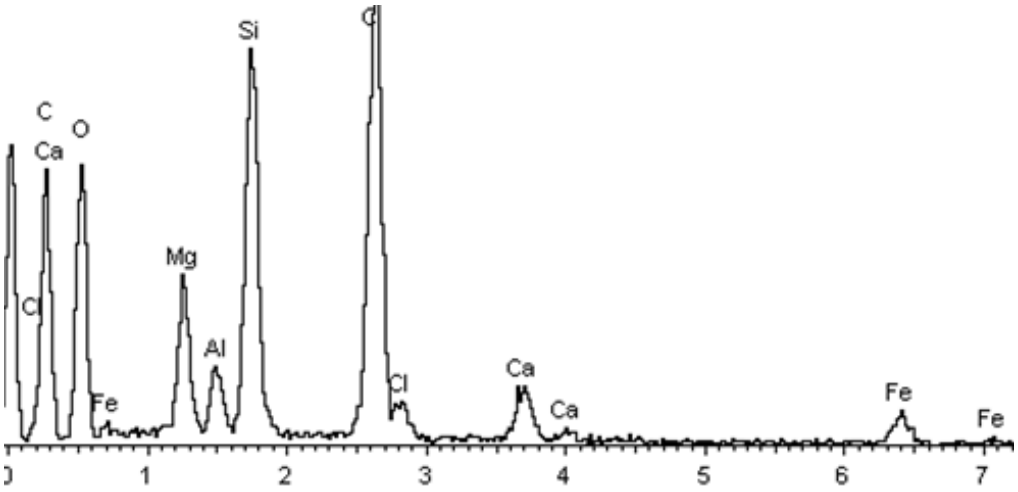


Figure 6.11: F6727 particle 3 elemental spectrum.

The particle seen in 6.12 is from a personal sample taken for a crusher operator at an aggregate rock (andesite) quarry. The physical length of the particle is > 5 µm and width < 3 µm which means that this particle is classified as a respirable fibre. The morphology is similar to erionite.

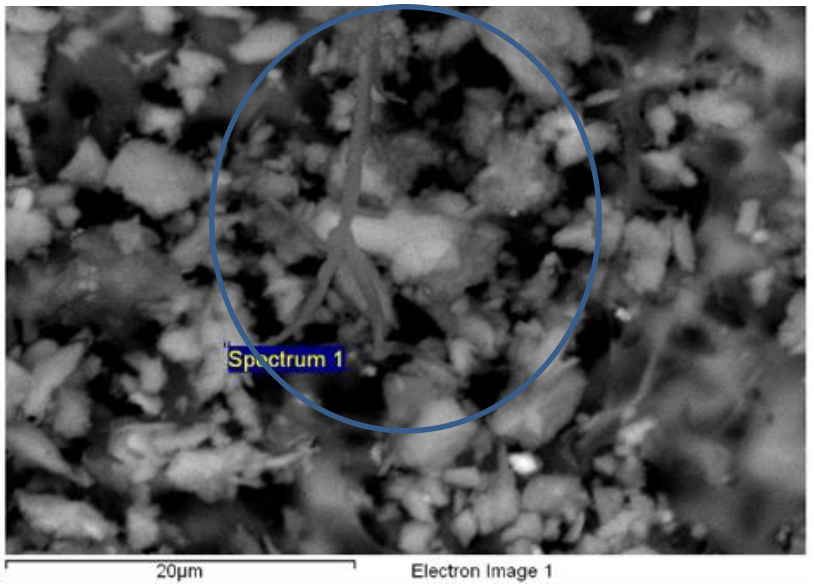


Figure 6.12: F6439 particle 1 micrograph.

Although the major elements for the micrograph (Figure 6.12), in Figure 6.13 are identified as silicon and oxygen indicating free silica, other identified albeit in minor quantities the elemental composition including sodium (Na), magnesium (Mg) and potassium (K) suggests that this a fibrous mineral silicate called erionite.

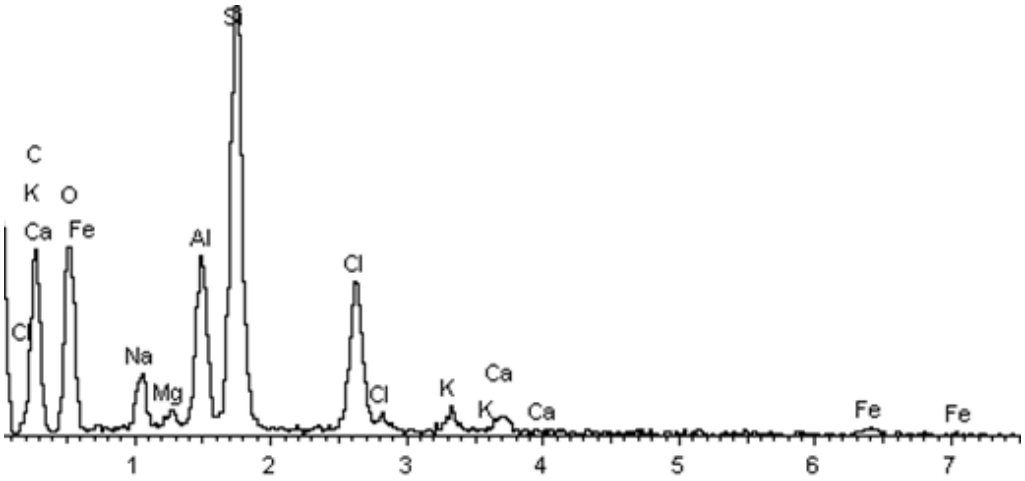


Figure 6.13: F6439 particle 1 elemental spectrum.

6.4 Discussion

From Figures 6.1 and 6.2 it can be seen that most of the particles had a physical diameter between 2 to 5 µm, which covers the size-range considered to be high-risk respirable as seen in Figure 6.14.

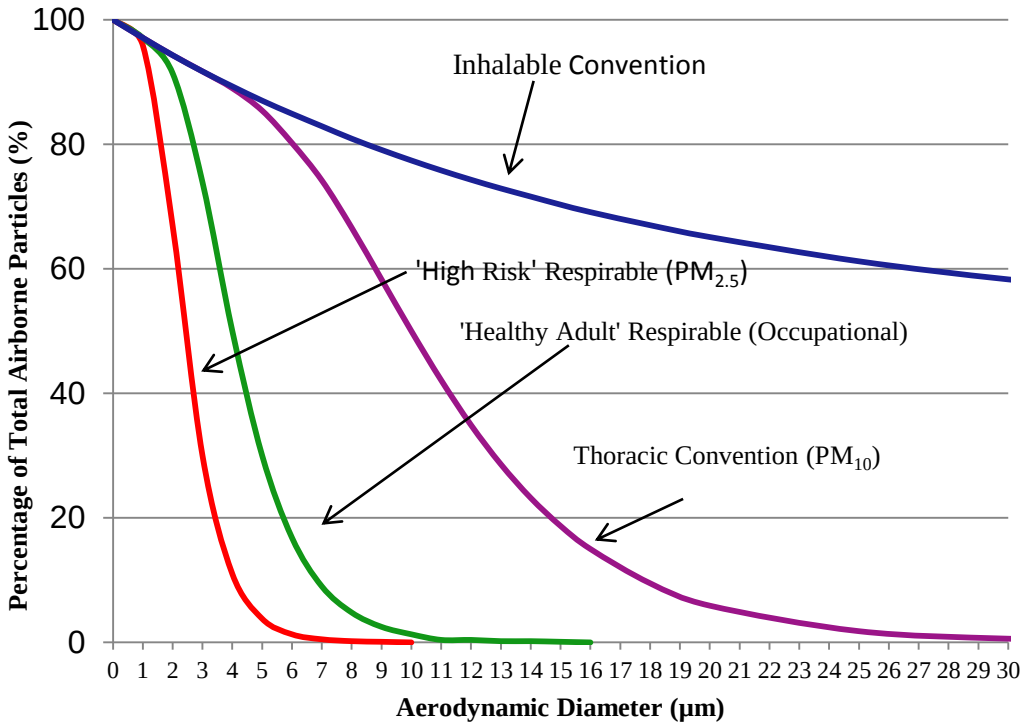


Figure 6.14: Comparison of sampling curves
(Source: adapted from ISO 7708, 1995, p7)

The exception is that the graph is for EAD. The use of EAD implies that density will play a dominant role in sampling efficiency, whereas the findings in this study suggest that shape will also influence the size distribution of particles sampled as the particles are not spherical. A case in point is provided in Figure 6.6 for a near spherical particle. The formula for converting physical diameter to EAD is straightforward because the only factor for the conversion is density, as shape will not influence conversion. On the other hand from Figures 6.8, 6.10 & 6.12 it can be seen that these particles are not spherical and a conversion can only be made if shape is factored in. ISO 13138 (2012, p.4) notes that:

> With coarse particles (aerodynamic equivalent diameter greater than about 0.5 μm) such as those found in the mining environment, the conventional respirable fraction and aerosol particles deposited in the gas-exchange region correlate well with the mean.

No reference is provided in ISO 13138 (2012) to qualify this statement. Due to the heterogeneous nature of particle morphology in mining and considering that shape will greatly influence behavior this statement is misleading. If the particles were spheres, as per stokes law, then the following formula will apply:

$$dpa = dps\sqrt{Pp}$$

Where *dpa* = Aerodynamic diameter

dps = stokes diameter μm

Pp = particle density, gm/cm^2

(Popendorf 2006, p.49)

As the median (physical) diameter of silica particles was 4.4 μm, applying the above formula equates to an EAD of 7.2 μm as per the following:

$$dpa = 4.4\sqrt{2.65} = 7.2 \text{ μm EAD}$$

This is far from what is expected, which is 4.25 µm EAD (SA 2009). Another factor is influencing particle size distribution is particle shape and reference is made to the following formula:

$$da = dg\sqrt{\frac{Pe}{\lambda Ps}}$$

Where da = Aerodynamic diameter

Ps = 1 g/cm^2

dg = particle geometric diameter

Pe = effective particle density in the same unit as Ps

(Hassan & Lau 2009, p.1252).

> 'The shape factor (λ) is defined as the ratio of the drag force of the particle to that of a sphere of an equivalent volume' (Hassan & Lau, p. 1252).

Elongated particles in this study have a length, diameter, and aspect ratio, which may be categorised as respirable fibres. Fibres have a greater likelihood to be entrained in the air and penetrate into the lung as respirable fibres. This means that shape will play an important role, which may explain why there are a greater proportion of larger particles in the respirable dust size range. This may also explain the anomaly indicated by Hedges et al (2013), and in fact the density of the respirable dust samples will not be close to 1, as previously suggested.

An unexpected finding was identification of a fibrous mineral particle with morphology similar to erionite. Erionite has a natural fibrous habit, is a mineral silicate, and is known to cause mesothelioma when inhaled at high enough concentrations (Dogan 2011). Preliminary investigation carried out to characterise and identify the source of this fibrous mineral shown in Figures 6.10 and 6.12, indicates that the mineral spectrum is similar to that shown in Figure 6.15 which is from a report comparing spectrums of erionite.

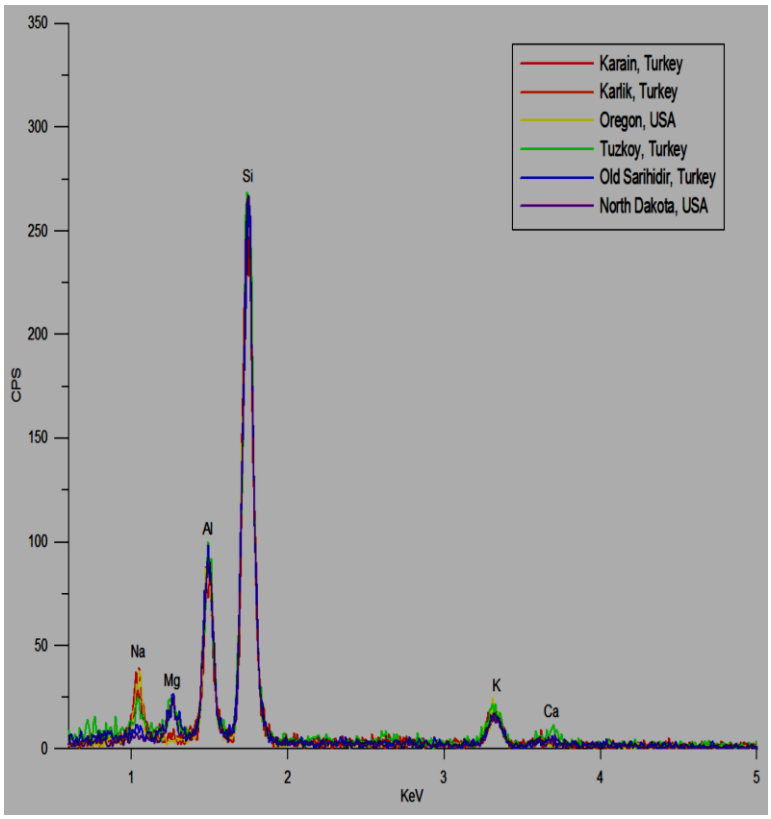


Figure 6.15: Spectrum of erionite for comparison (Source: United States Department of the Interior and Geological Survey 2010 p.7)**.**

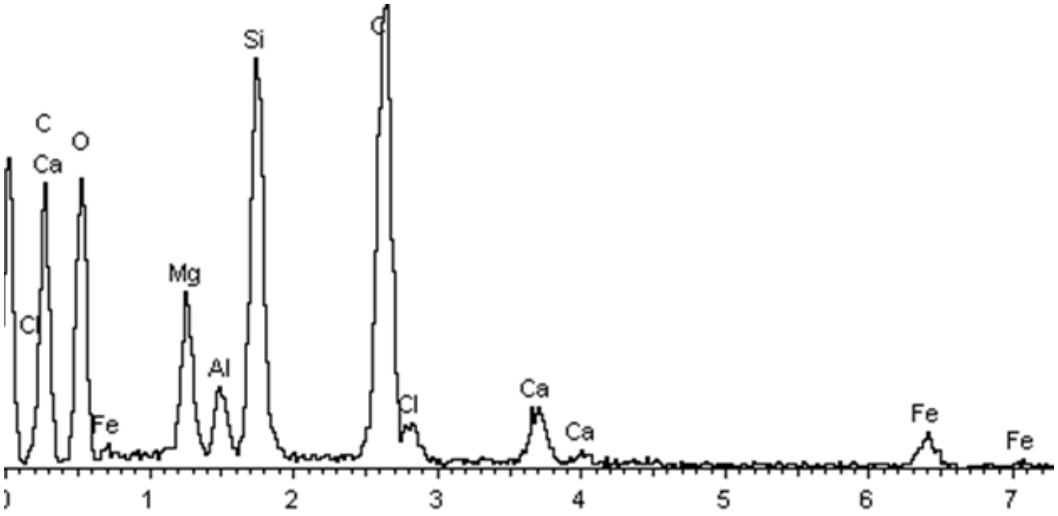


Figure 6.16: **Elemental spectrum of fibrous mineral particle in sample F6439 (reproduced from Figure 6.13 for ease of comparison).**

Morphology seen in Table 6.4 for particles in samples F6727 & F6439, is similar to erionite.

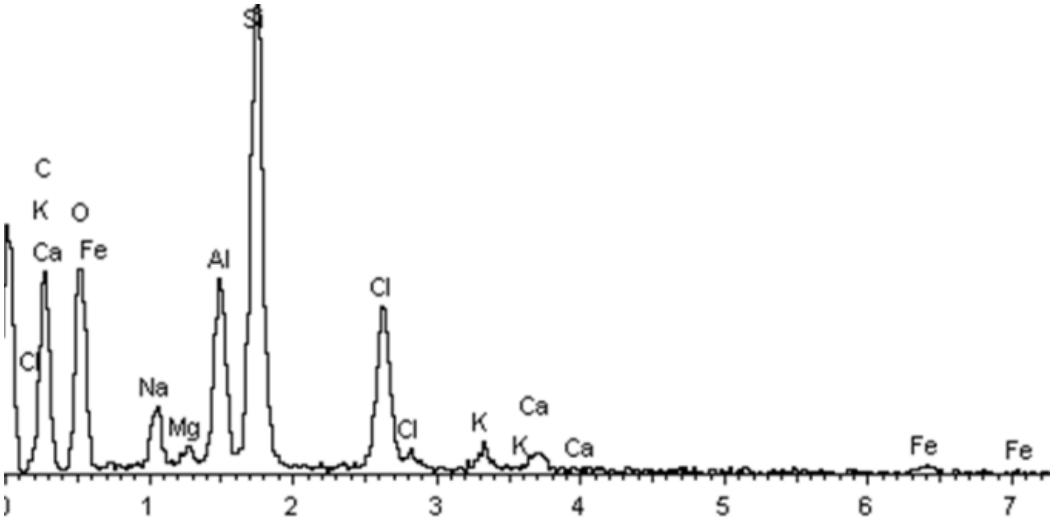


Figure 6.17: Elemental spectrum of needle like mineral particle in sample F6727. Erionite is hazardous because exposure to erionite in airborne dust is known to cause mesothelioma (Dogan 2011). As can be seen in Figure 6.4, for studies carried out in Turkey, and the USA, there is a similar spectrum for silica aluminium and magnesium with the spectrum shown for erionite.

6.5 Conclusion

Analysis by electron microscopy of respirable dust and respirable crystalline silica provides an insight into the particle size distribution and physical form of the different particle sizes. Most of the silica particles are less than 5 μm in physical diameter. The literature notes this size fraction as being the most hazardous to lung health. The empirical nature of EAD is questioned, and the context in which it is used is over-simplified, especially as airborne particles do not exist as perfect spheres. Although density must be considered in converting physical diameter to EAD, findings agree with the literature. Shape will greatly influence how particles penetrate and are deposited into the alveolar region of the lung. These particles are not perfect spheres, and some of which are

elongated and rod-like. The use of EAD that does not match workplace aerosols, nor consider shape, overly simplifies the empirical EAD model and AS2985-2009 sampling efficiency curve. The findings demonstrate that larger length particles have been collected in the cyclone sampler influencing the particle size distribution curve. Rod-like / fibrous / elongated particles, resulting in 'frustrated phagocytosis', will be more hazardous due to increased surface area and aspect ratio.

The percentage of RCS in respirable dust is important. Graphically the curve is skewed towards the smaller size fraction of the curve as % of RCS in respirable dust increases. This suggests that the risk from exposure is not linear. It also demonstrates that both RCS measurement and particle size analysis may be required when proving the efficacy of air cleaning devices such as the RESPA®.

Finding erionite in respirable samples analysed in this study, and the association of this fibrous particle with known causes of mesothelioma is an important finding for the health management of mine workers. Follow-up research needs to be carried out on samples collected in the current study thought to contain erionite. Confirmation of the presence and extent of erionite in samples, using elutriation and high resolution scanning electron microscopy (SEM), will assist in determining the extent of health risk to quarry workers in Queensland. X-ray diffraction (XRD), Inductively coupled plasma-mass spectroscopy (ICP-MS) or X-ray fluorescence can also be used. Erionite characterization guidelines are provided in Dogan & Dogan, 2008.

To view micrographs, elemental scans, and particle size distributions for all filter samples refer to Appendix I.

Chapter 7.0 Discussion

7.1 RCS exposure and impact on lung health

A correlation of RCS exposure at or near the current SWA-ES showing loss of lung function below the LLN is demonstrated. The results of this study show the importance of lung function measurement (spirometry).

The AIOH, (2009, p.7) states that:

It is becoming evident that there is not a substantiated nor observable adverse effects level (NOAEL) at which it can be categorically stated that exposure to crystalline silica has no adverse health effects. The literature is demonstrating risks to health at levels previously considered as being acceptable.

This study confirms that the current SWA-ES is not suitably protective and reinforces that this occupational exposure limit is not a fine dividing line between safe and unsafe exposure. The study also confirms the importance of carrying out regular health surveillance, especially for high risk exposure groups, such as stone masons, crusher operators, and excavator saw operators in dimension stone mines.

Townsend et al. (2011) notes that, as specified in the OSHA (2008) Special Emphasis Program, components of health surveillance evaluation should include:

- Occupational and medical history (questionnaire)
- Physical examination
- Purified protein derivative (PPD) tuberculin skin test
- Chest radiography
- Spirometry

In OSHA (2008) there is also a recommendation that a respiratory questionnaire be included and the author agrees with that position based on the data reported in the current study.

In the United Kingdom there is general consensus to support baseline assessments of respiratory health for potentially RCS-exposed workers with subsequent annual assessments (HSL 2010). HSL (2010, p.7) states that:

> The purpose of medical surveillance is to detect early any potential adverse health effects from workplace exposures. If adverse health effects are detected early enough, then interventions can be introduced to potentially lead to disease prevention or to slow the progression of an established disease process.

More recently the HSE (2015) have published guidance for occupational health professionals; health surveillance for those exposed to RCS which requires baseline and then annual health surveillance for high risk workers which include stone workers and quarry workers. Clear guidance is provided and abnormal lung function test results are defined which includes an FEV1 % of predicted < 80% (HSE 2015). The findings from this study support this statement by demonstrating the value of spirometry coupled with exposure monitoring. The test results for workers in these studies showed 14 workers with abnormal lung patterns. Of these, 7 had moderate lung function losses as demonstrated FEV1 % of predicted scores (refer to Tables 5.8, 5.9, 5.10 & Figures 5.13 – 5.19 in Chapter 5). For the workers with moderate lung function loss, 5 had obstructive lung disease patterns (Figures 5.13, 5.14, 5.17, 5.18, 5.19) indicating COPD (emphysema & chronic bronchitis) and 2 showing restrictive lung disease patterns (Figures 5.15 & 5.16). A restrictive lung function test result may indicate interstitial lung disease (silicosis).

Although changes in lung function may not be seen in simple silicosis, changes in lung function are likely to occur in workers who have been exposed to intense levels or excursions of airborne dust. Spirometry can indicate that

further investigation is warranted and that the worker may be exposed to elevated airborne concentrations of airborne respirable dust and crystalline silica prompting the need for urgent control. Although an arbitrary general LLN is used at 80% of the predicted value, the ACOEM recommends that this should not be used in an occupational health setting (Townsend et al. 2011). On the contrary, this measure can be used as a benchmark. It provides a trigger for follow-up to investigate both exposure, and efficacy of control, which will prompt further action to prevent the progression of lung diseases for mines, quarries and exploration site workers. This statement is also reinforced by guidance released by the HSE (2015). Townsend et al. (2011) have recommended that there should be increased attention to the interpretation of lung function over time or longitudinally. Results from the current study support this position. Further follow-up, including assessment of chest x-rays by trained B readers for the workers in this study may strengthen the findings. Health surveillance that includes dust monitoring of quarry workers over time (longitudinally) will add to the weight of evidence that their respiratory health is being impacted by exposure to RCS.

For workers exposed to RCS $\geq$ 0.04 mg/m^3 of RCS, there was an observable increase in smokers showing symptoms of obstructive disease which is consistent with the literature (Hnizo et al. 2003). An example is shown in Table 7.1. Comparing smokers with those workers who had never smoked, the increase in silicosis is close to double for early signs of silicosis (category 0) and increases to about six times for more advance (category 1) silicosis.

Table 7.1: Distribution of age and smoking status from a follow-up survey showing silicosis profusion category (Source: IOM Research report TM/01/03 February 2001 p.37)

Profusion category								
	0		1		2		All	
Age at survey	n	%	n	%	n	%	n	%
<40	57	15	2	2	0	0	59	11
40-49	48	12	7	6	4	8	59	11
50-59	86	22	24	22	13	28	123	22
60-69	123	32	42	38	22	47	187	34
70+	75	19	36	32	8	17	119	22
Smoking status								
Smoker	167	43	61	55	21	45	249	46
Ex-smoker	152	39	40	36	18	38	210	38
Never smoked	70	18	10	9	8	17	88	16
Total	**389**	**100**	**111**	**100**	**47**	**100**	**547**	**100**

Studies of North American hard rock miners found a different pattern of lung disease based on lung function in smokers compared to non-smokers. For non-smokers the decrease in lung function and pattern was suggestive of restrictive disease. Smokers on the other hand had a pattern which indicated emphysema which is an obstructive lung disease (Hnizo et al. 2003). Hnizdo et al. (2003) emphasized that smoking increases the potential for emphysema when there is concurrent exposure to silica dust. Hnizo et al. (2003) also reported that in a study of South African Gold Miners airflow obstruction was present in silica exposed workers without radiological signs of silicosis. Further analysis correlated computed tomography (CT) findings for silicosis and emphysema with pulmonary function in silica exposed workers (Hnizo et al. 2003).Conducting high resolution CT scans, for workers as a follow up to this Queensland study, may reveal that there are cases of silicosis that have not been previously diagnosed.

7.1.1 Exposure to RCS and COPD

Quartz has been shown to cause COPD following direct placement of 10 mg & 20 mg into the trachea of laboratory rats. Once the rats were killed after 30 days, morphological changes observed included evidence of air-flow obstruction for 10 mg & 20 mg doses. Emphysema and thickened airway walls were observed. Early stage silicosis nodules were also observed in the higher exposed rats (Wright et al. 1988). This suggests that early detection of emphysema and subsequent action may reduce the risk for the onset of silicosis. These doses administered to rats are relatively high much higher than what would be experienced by workers.

In a study of white South African gold miners, where X-rays showed signs of silicosis, the lung function including FEV1 reduced over time with cumulative dust exposure. The average cumulative dust exposure resulting in loss of lung function estimated for a 50 year old miner exposed for 24 years was 0.6 mg/m^3 and loss of lung function for FEV1 was 236 mL (CI 135 to 338). As the miners got older there was a steeper decline.

Where x-ray signs of silicosis were not present for Swedish granite workers (followed for 12 years) exposed to a mean cumulative respirable silica dust of 7.2 mg/m^3.year (which equates to 0.6 mg/m^3), workers had a greater loss of lung function FEV1, when compared to controls. A combined international study, for concrete workers, potato sorters, and pottery workers shows a loss of lung function as FEV1 & FEV1/FVC with cumulative dust exposure, in both smokers and non-smokers. The study noted that for relatively young silica dust exposed workers, the loss of lung function was still obvious, where there were no signs of silicosis. The average exposure for these workers was 0.1 to 0.2 mg/m^3 of RCS (Hnizo et al. 2003). This emphasizes the importance of spirometry as a predictor of more serious respiratory health changes, and a way to prevent the progression of COPD and early signs of silicosis.

Hnizo et al. (2003) refer to three epidemiological studies to correlate findings for a South African Gold Miners study which compared dust exposure and emphysema found at autopsy. Emphysema scores (ES) represented the percentage of lung affected by emphysema as determined on sections of lung. It was shown that an ES score from high dust exposed workers for an exposure of about 20 years increased the risk of emphysema between 3.5 times and 12.7 times for high dust exposed workers compared with low dust exposed workers. In addition it was estimated that the mean ES score, adjusted for the dust exposure and age was 7.1 for non-smokers and 36.5 for smokers of 20+ cigarettes a day which is a score 5 times higher for dust exposed smokers as compared to dust exposed non-smokers (Hnizo et al. 1993).

From this Queensland study, referring to Chapter 5, Figure 5.11: more RCS exposed $\geq$ 0.04 mg/m^3 smokers showed greater lung function patterns than RCS exposed non-smokers. This difference was not as pronounced when smoker and non-smoker lung function patterns were compared for RCS exposures < 0.04 mg/m^3.

The model provided by Hnizo et al. 2003, in Figure 7.1 provides a visual comparing ES scores with FEV1 % of predicted which emphasizes the importance of early intervention using spirometry as a measure. The model also shows the decline in FEV1 % of predicted with increasing age which may also be associated with duration of exposure. This is consistent with the findings in this Queensland study shown in Chapter 5, Figure 5.21 where comparison loss of lung function measured as FEV1 % of predicted, showed greater loss with years in industry.

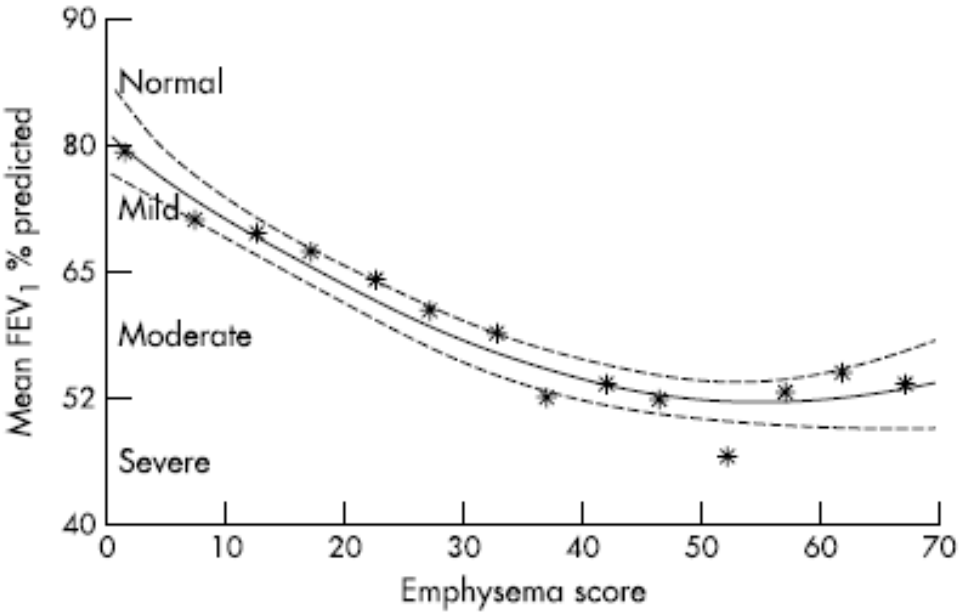


Figure 7.1 Observed and estimated mean FEV1 % of predicted and 85% mean CI in relation to emphysema score found within 5 years of post-mortem examination in 726 South African gold miners. In-life compensation categories (normal, mild, moderate severe) are indicated (Source: Hnizdo & Vallyathan 2003, p.240).

7.1.2 Spirometry

Spirometry can be used to assess lung function, and can also be used to differentiate obstructive (such as COPD) from restrictive respiratory disease, which includes silicosis.

FEV1 (forced expired volume in 1 second) is the volume expired in the first second of maximal inspiration and a measure of how quickly full lungs can be emptied (Johns et al., 2007). The most commonly seen defect is airflow obstruction, which is characterised by reduced expiratory flows (for example COPD and asthma).

To understand the level of inter-individual variability and distribution of lung function tests for similar exposure groups, a minimum number of workers are required for each SEG. In this study one of the shortcomings in lung function testing was the limited number of workers in each SEG. Mining operations that

are larger than quarries and dimension stone mines, with similar mineralogy and a greater number of workers would allow a better analysis of variance. Nevertheless a correlation ($p<0.05$) was shown between exposures ranging from <0.02 mg/m^3 to 0.20 mg/m^3 and loss of lung function even though there are a limited number of workers in this study.

The Kolmogorov goodness of fit test showed that the curvilinear relationship between FEV1 % of predicted and RCS exposures up to 0.2 mg/m^3 was significant. There is an anomaly when the higher exposures for the fitter and sand plant operator are factored in, where the same relationship was not shown (refer to Figure 5.2). The Sand Plant Operators (dry) had an FEV1 % of predicted lung function (against normal) range of 82 - 113, which is large and the fitters range for RCS exposures is 0.01 – 0.78 mg/m^3 is also large.

None of the sand plant workers were current smokers and 2 out of the 4 workers were quite young, 23 and 24 years old. The older worker who was 40 and a former smoker had a lung function FEV1 % of predicted of 82 which is approaching the LLN. The fitter's exposure to RCS would be expected to be highly variable as tasks carried out, and locations worked day to day, will greatly vary as demonstrated by a high RCS exposure GSd. of 6.5. As the plot for RCS results greater than 0.2 mg/m^3 didn't fit the curve, shown in Figure 5.2, the decision was made to focus statistical analysis on those SEGs with an average exposure < 0.2 mg/m^3.

7.2 RCS

7.2.1 RCS Potency

The sand plant operator was not exposed to freshly crushed crystalline silica which may be one reason, apart from those already discussed, as to why the same loss of lung function was not observed in this SEG (refer to Tables 5.2 and 7.2). On the other hand, the excavator and saw operator was exposed to finely ground powder and the median physical diameters for respirable particulate matter ranged from 2.3 – 4 µm.

The sample taken inside the cabin with a RESPA® recirculation unit resulted in a reduction of the RCS median physical diameter to 2.3 µm (Figure 6.5). This means that for this excavator saw activity, RCS potency is increased due to reduced particle size and the material being finely ground with no water suppression. The excavator and saw operator (code A3) had an RCS average exposure at 0.25 mg/m^3 with a maximum at 0.32 mg/m^3 - refer to Table 5.12. This worker's lung function test results are 62 FEV1 % of predicted and 58 FEV1/FVC % of predicted (Figure 5.14) which means that his lung health is close to being severely affected. This reinforces the need to ensure that these high risk jobs such as the excavator & saw activity in dimension stone mines have more effective controls to reduce the risk of worker's lung health being severely affected.

Table 7.2: Potency matrix (Adapted from HSE (2002) EH 75/4 p.7)

Factors	Comment	Situations
Particle size	Enhances potency	Grinding and abrasive processes
Dry and freshly cut	Reference point to compare potency	Drilling, crushing
Wetting	From dust suppression	Wet extraction processes
Aged	Reduces potency	No abrasion or grinding
Presence of clay	Aluminium reduces potency	Mines extracting low rank coal

7.2.2 RCS Sampling and analysis

Being able to measure RCS accurately at low enough concentrations is very important so that exposure profiles can be established for a range of work activities. If too many results are less than the limit of quantitation an accurate assessment of average exposure and confidence intervals is not possible. Reference is made to Harper et al. (2014), who found that Analysis of Proficiency Analytical Testing (PAT) results between 2003 and 2013 indicated that the variation in RCS analysis is less than it was in the period 1990–1998.

Harper et al. (2014) qualifies this by saying that it is partly because of a change in sample production procedure and because the colorimetric method has been phased out, although quality improvements in the x-ray diffraction (XRD) or infrared (IR) methods may have also played a role. Harper et al. (2014) also noted that matrix interference does not lead to biases or substantially larger variances for either XRD or IR methods. Notwithstanding PAT samples are not produced below 40 µg as variance (or uncertainty) will be much greater at lower masses. PAT data from lower mass loadings will be required to evaluate analytical performance if exposure limits are lowered without change in sampling method (Harper et al. 2014).

Harper et al, (2014, p.D157) noted that:

> Task-specific exposure measurements for periods shorter than a full shift typically result in lower mass loadings and the quality of these analyses would also be better assured from being within the range of PAT mass loadings.

For an 8-hour sample, a 40 µg mass loading at 2.2 L/min equates to about 0.04 mg/m^3. This is the lowest standard against which laboratories have been compared as part the PAT inter-laboratory quality assurance program.

When the RCS distribution from the Queensland study for data in group B (RCS $\geq$ 0.04 - $\leq$ 0.08) mg/m^3 is plotted (shown in Figure 7.2), results demonstrate that there is a good log-normal fit of RCS concentrations above 0.04 mg/m^3. For results between 0.04 mg/m^3 and limit of quantitation which is 0.02 mg/m^3 the degree of variability is much greater. The data from the Queensland study therefore confirms that lowering the SWA-ES to the same occupational exposure limit as the ACGIH-TLV of 0.025 mg/m^3 is not technically feasible as the variability at this level will be too high (refer to Chapter 2 Figure 2.17 & Table 2.8) & Figure 7.3.

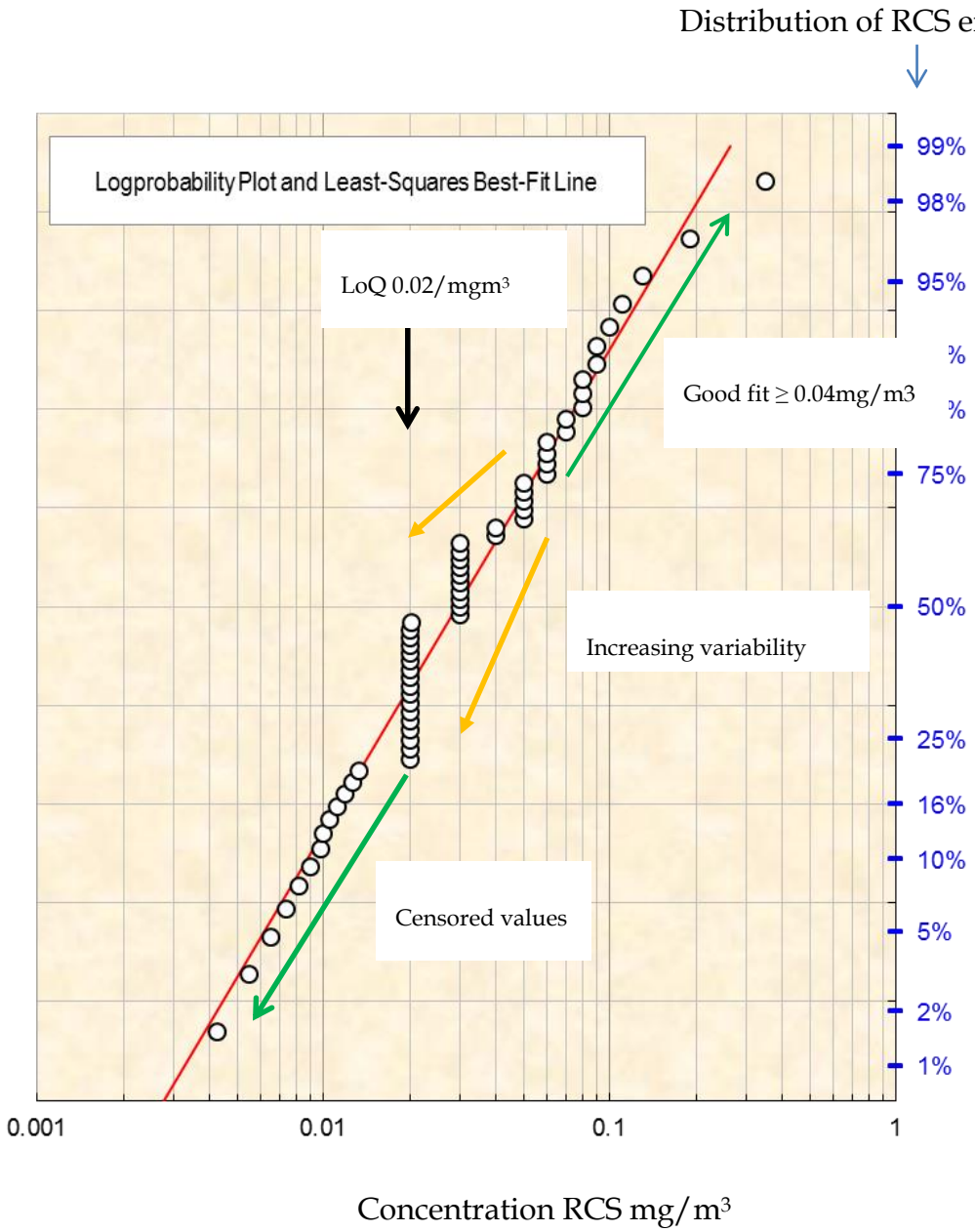


Figure 7.2 Log-probability plot and least squares best fit line for RCS exposures for group B data (medium ≥ 0.04 mg/m³ - ≤ 0.08 mg/m³)

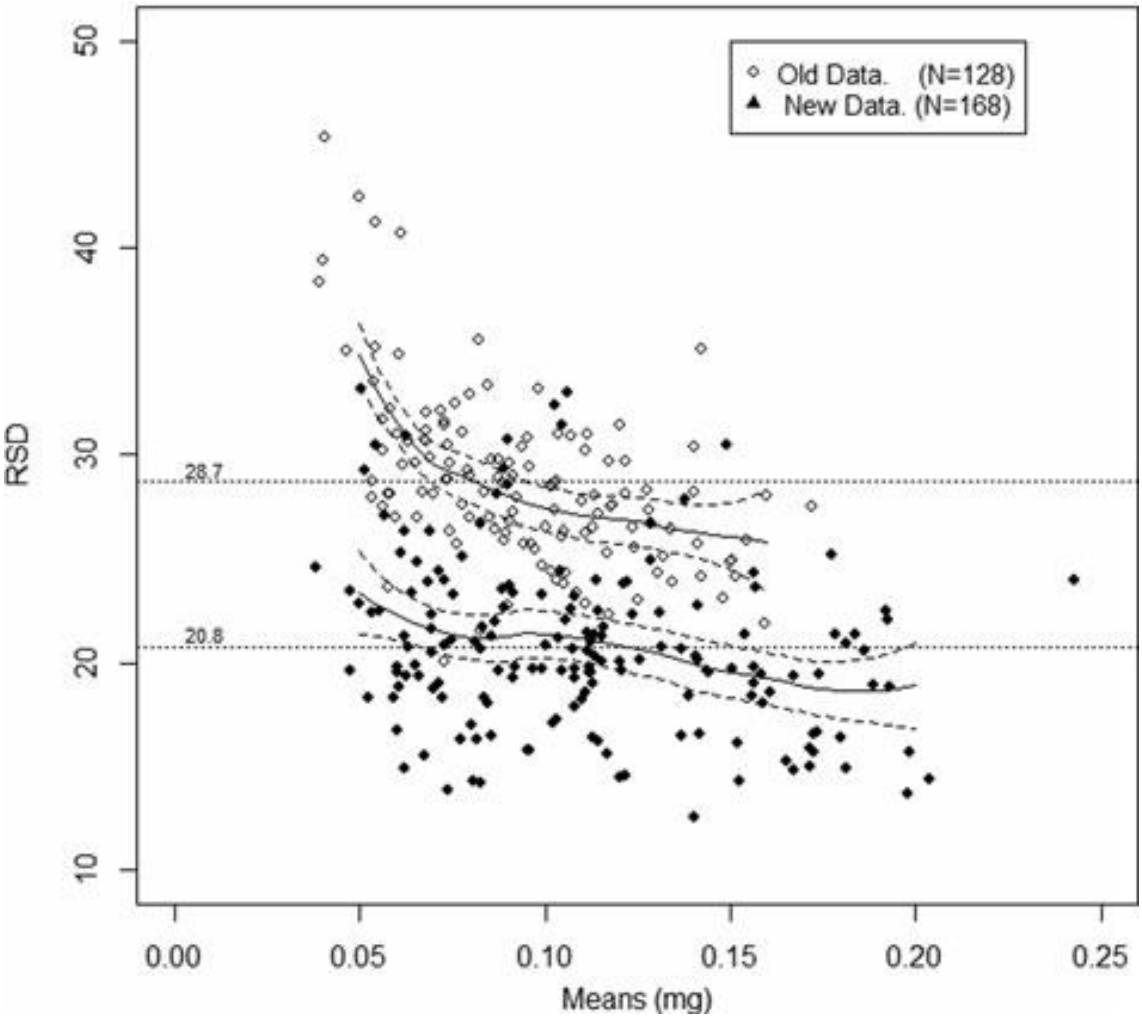


Figure 7.3 Comparing old data and new data. (Relative standard deviation (RSD) of RCS PAT Samples from Rounds 152–194, 2003–2013 (New data), compared to Rounds 102–132, 1990–1998 (Old data), according to all-laboratory mean mass loading (Source: Harper, Sarkisian & Andrew 2014, p.D159).

7.3 Respiratory questionnaires

Chapter 5 demonstrated the importance of using respiratory questionnaires as part of health surveillance. SWA (2013c) recommended administering a standardised respiratory questionnaire and have provided two examples: either the international Union Against Tuberculosis' Bronchial Symptoms Questionnaire 1986 or the Medical Research Council's (1986) Questionnaire on Respiratory Symptoms (SWA 2013c).

SWA (2013c) also noted that there is a general consensus for annual assessment with respiratory questionnaire and lung function tests to look for lung function changes over time. This is supported by the current study where symptoms of cough bringing up phlegm, breathlessness (dyspnoea) and wheeze have been reported by those workers in similar exposure groups (SEGs) with relatively higher RCS exposure. Findings from this study also found that 27% of workers reported being breathless when hurrying on level ground or walking up a slight hill, while 10% reported they are short of breath walking with other people on level ground (refer to Chapter 5, Figure 5.21). In addition, 7 of the 44 workers with spirometry showed lung function loss of moderate severity, whilst 4 of the 5 workers with obstructive lung disease patterns reported symptoms of breathlessness indicating emphysema. The two workers with restrictive lung function patterns (moderate severity) did not report breathlessness.

According to Cotes & Chinn (2007, p.388),

> The Medical Research Council Questionnaire (MRCQ) was developed by researchers at the Medical Research Council, UK, as a tool to study respiratory epidemiology in communities and occupational exposure groups.

Cotes & Chinn (2007) also noted that the grades of breathlessness are weakly correlated with forced expiratory volume (FEV). Correlation is higher with ventilation during sub-maximal exercise and with quality of life, as assessed by the quality of life questionnaire. The St George's Respiratory Questionnaire for COPD Patients may be useful in subsequent follow up to this study to measure health impairment in patients with asthma and COPD (Jones & Ford, 2008). Carpenter et al. (1989) indicated that subsequent mortality ratios are greater for those who report morning cough, morning phlegm, and breathlessness when walking, and wheeze most days or nights. Carpenter et al (1989) reported that periodic symptoms predict subsequent mortality from chronic obstructive airways disease. Reversible airflow obstruction may be a precursor to progressive and irreversible decline in lung function. In other words where the

questionnaire determines periodic symptoms this information can then be used to prevent long term irreversible respiratory disease.

According to Tidy (2014, p.1),

> A diagnosis of COPD should be considered in patients over the age of 35 who have a risk factor (generally smoking) and who present with one or more of the following symptoms:
>
> - Exertional breathlessness,
> - Chronic cough,
> - Regular sputum production,
> - Frequent winter bronchitis,
> - Wheeze.

Tidy (2014, p.1) also recommended that,

> 'The Medical Research Council (MRC) dyspnoea scale should also be used to grade the level of breathlessness'.

Table 7.3: Medical Research Council (MRC) Breathlessness Scale (Source: Stenton 2008, p.226)

Grade 1	Not troubled by breathlessness except on strenuous exercise.
Grade 2	Short of breath when hurrying or walking up a slight hill.
Grade 3	Walks slower than a contemporary on level ground because of breathlessness or has to stop for breath when walking at own pace.
Grade 4	Stops for breath after walking about 100 metres or after a few minutes on level ground.
Grade 5	Too breathless to leave the house, or breathless when dressing and undressing.

The MRC breathlessness scale can be used to categorise grades and to identify interventions such as pulmonary rehabilitation in COPD. The scale is also complementary to FEV1 in describing disability in patients with COPD (Stenton 2008). Over one third (37%) of respiratory questionnaires indicated that the symptoms of breathlessness were between grades 2 and 3.

7.4 Particle size distribution and shape

To fully understand the true nature of cyclone sampler collection efficiency and how RCS particles effect the lung, it is proposed that a predominant factor leading to sample collection for the larger particles identified in this study is shape. The micrographs of a sample collected from an excavator saw operator, at a stone forming mine, showed that some particles have needle-like morphology (Table 6.4, sample F6727). Champion & Mitragotri cited by Hedges et al. (2007) noted that the shape of a particle in the lung plays a dominant role in the capacity of macrophages to engulf and remove the particle. It is postulated that for the current study, due to the number of elongated particles, some of which are fibrous minerals, the shape will greatly influence deposition. Once in the lung, fibrous dusts such as asbestos, and other mineral fibres such as erionite, have been shown to be hazardous to health mainly because of their shape. Particles with diameter <3 μm in diameter and >5 μm in length with an aspect ratio (length to width ratio) of more than 3:1 are classified as respirable fibres (SWA 2009), which present unique health problems. For freshly cut respirable silica dust, once in the lung, macrophages will take longer to engulf these particles, prolonging exposure between the active cytotoxic particle and macrophage surface, increasing the likelihood of cell death. Phagocytosis by alveolar macrophages is more active for particle diameters 0.5 – 2 μm (Gregoratto et al. 2010). Calculating elongation factors for all measured particles in this study and then plotting elongation factors against physical diameter may confirm that the larger particles are more elongated, which may also explain the deviation between EAD and physical diameter, especially for the particles between 4 and 12 μm. The analysis also indicated that as the percentage of RCS in respirable dust increases, there is a corresponding reduction in the physical median diameter of the particles. This is demonstrated in Table 6.2, where the median physical diameter for dust generated during trenching/cutting of sandstone was lower than for exposure groups where the % of RCS was lower. The correlation shown in Figure 6.4 confirms this observation.

An unexpected finding in this study was the identification of particles that had fibrous & needle-like morphology shown in Chapter 6, Figure 6.12. Further investigation is required to characterise the shape, size and mineral content of these particles, and to determine if certain particle shapes result in frustrated phagocytosis more than others.

It is considered likely that the combination of size, shape and mineral content of RCS particles, rather than size alone, might lead to increased pathogenicity.

The term frustrated phagocytosis refers to the inability of a macrophage to fully engulf a particle and remove it from the lung, which can increase the risk of fibrosis. The more elongated the particle, the longer it takes for phagocytosis to occur (Champion & Mitragotri 2006). Where there is longer exposure time for the macrophage to free radicals from the freshly cleaved quartz crystal the initiation of steps leading to fibrosis is exacerbated.

It is proposed that a combination of characteristics results in RCS toxicity, and that morphology must be considered as an important factor. More research is required to investigate this proposition.

7.5 Suspected erionite

The detection of mineral particles by scanning electron microscopy (SEM) shown in Chapter 6, have been compared with photographs and a spectrum for erionite, produced by the United States Department of the Interior and Geological Survey (2010) shown in Figure 6.4. Comparison suggests that the mineral fibres are erionite. If erionite is confirmed there may be concern which depends on the level of exposure to airborne respirable erionite fibres. Erionite is a non-asbestos mineral which belongs to a group of aluminosilicate minerals known as zeolites. The natural form of erionite is fibrous, and when inhaled into the lung these fibres behave in the same way as asbestos causing the same radiological changes to the lung. 9.3% of villagers living in zeolite exposed villages in Turkey have been shown by x-ray to have fibrous thickening on the

lining of the lungs (pleural plaques). The detection of pleural plaques on chest X-rays typically indicates exposure to asbestos. Emri et al. (2002), suggested that these pleural plaques are caused by breathing in erionite dust.

Emri et al. (2002 p.253), also noted that:

> 'In the zeolite villages of Karain, Tuzköy, and Saridir, malignant mesothelioma is responsible for more than 50% of deaths'.

Experimental studies have shown that erionite has 300 – 800 times more carcinogenic potency than chrysotile (asbestos), and 100 – 500 times more potency than crocidolite (asbestos) when given through intra-pleural routes (Cathew cited in Emri et al, 2002). The US Center for Disease Control and Prevention noted that residents of some Turkish villages, where erionite-containing rock was used to construct homes, have a high risk for development of malignant mesothelioma (Weissman & Kiefer 2011). Until recently, erionite was not generally considered to be a potential hazard in North America, in part because relatively little risk for exposure was seen. However, evidence has slowly accumulated linking exposure to erionite with serious adverse health effects, suggesting that some workers may have a greater potential for exposure than previously recognized (Weissman & Kiefer 2011).

According to Dogan et al. (2011, p.598),

> 'Although exposure to erionite is less widespread, it is more potent than asbestos in causing mesothelioma'.

Follow-up investigation should be carried out to further characterize the mineralogy for the fiber type minerals determined in this study.

In Dunn County, North Dakota, it has been reported by Carbone et al. (2011, p.13618),

> 'That for over 30 years, more than 300 miles of roads were surfaced with erionite-containing gravel'.

To determine potential health implications, Carbone et al. (2011) compared erionite from the Turkish villages to that from North Dakota (ND). Carbone et al. (2011) evaluated airborne point exposure concentrations. It was found that erionite concentrations measured in ND along roadsides, indoors, and inside vehicles, including school buses, equaled or exceeded concentrations in Boyali, a village in the District of Sinapasa, Afyonkarahisar Province, Turkey. It was noted that 6.25% of all deaths in this village are caused by Malignant Mesothelioma (MM).

Carbone et al. (2011, p.13168), noted that,

> 'Considering the known 30- to 60-y latency for MM development, there is reason for concern for increased risk in North Dakota in the future'.

Follow-up research needs to be carried out on samples collected in the current study thought to contain erionite.

Confirmation of the presence and extent of erionite by elutriation and high resolution scanning electron microscopy (SEM), will assist in determining the extent of health risk to mine workers in Queensland. As discussed in Chapter 6 X-ray diffraction (XRD) can also be used, or Inductively coupled plasma-mass spectroscopy (ICP-MS) or X-ray fluorescence. Erionite characterization guidelines are provided in Dogan & Dogan, 2008.

Chapter 8 Conclusion

8.1 Exposure assessment

There are approximately 55,000 workers employed in Queensland mining, and about 268,000 in the Australian mining industry, and mining directly employs 2.3% of the total workforce, and accounts for 10.2% of Australia's Gross Domestic Product (GDP) (Australian Government, Department of Employment, 2014).

If exposures to RCS are not controlled, through prevention, the hidden costs to worker health and the economy will be high. A survey by DME (2009a) concluded that workers in mining throughout Queensland may be at risk from exposure to RCS and associated adverse health effects (DME 2009b). The findings from this research has quantitatively confirmed that exposure to RCS is adversely affecting the lung health of quarry and dimension stone workers. Qualification is provided by exposure measurement in parallel with the testing of lung health.

A high proportion (32%) of the sampled workers demonstrated restrictive and obstructive lung function patterns of varying severity.

Results from personal exposure monitoring for RCS revealed that 24% of samples collected exceeded the SWA-ES of 0.1 mg/m^3 (8-hr TWA) at many sites as shown in Figure 8.1.

A correlation of the results (trend test p=0.0013) demonstrates a loss of lung function even for exposures at the current SWA-ES. This shows the current SWA-ES of 0.1 mg/m^3 is not sufficiently adequately to protect worker's health.

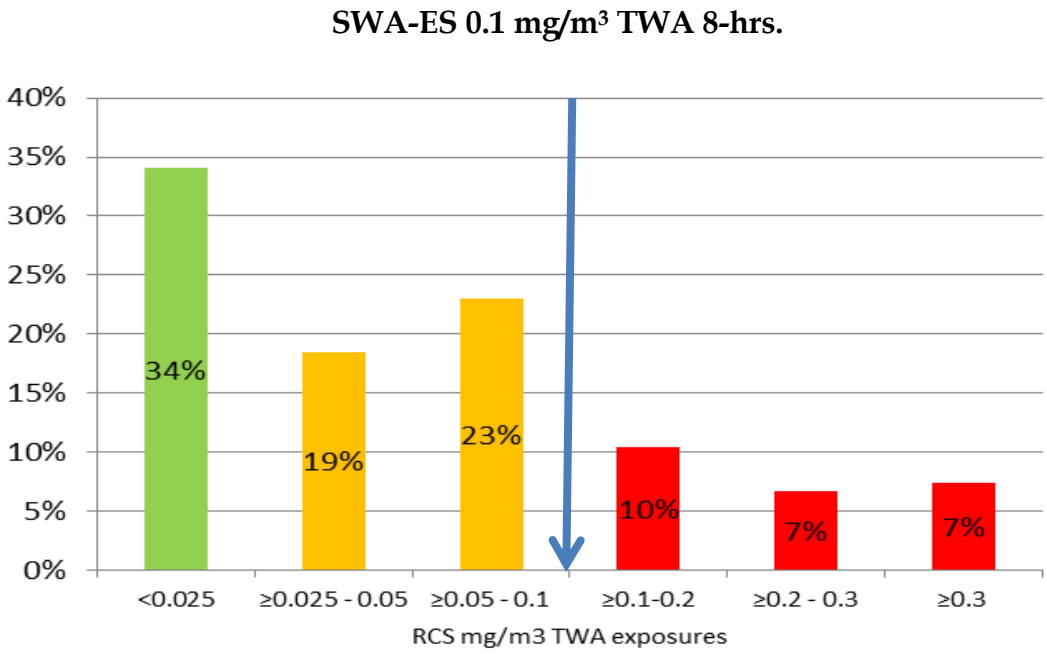


Figure 8.1: Percentage of personal exposure results to RCS that fall within each exposure band.

When attempting to understand the risk from exposure resulting COPD, it has been suggested that the onset of COPD symptoms will occur at RCS exposures less than that considered to cause silicosis.

Eleven of the workers in this Queensland study (about 25%), showed a lung-function pattern indicating obstructive disease. Most of these were smokers and 50% of smokers exposed to ≥ 0.04 mg/m³ RCS, showed symptoms of obstructive lung disease, whereas the same was not observed for smokers or non-smokers exposed to RCS < 0.04 mg/m³.

This study indicates that workers are not adequately protected when working in an excavator with saw attachment or while cutting and trenching through sandstone rock. Installation of a Sy-Klone International RESPA® unit that combines the technology of a motorized pre-cleaner, filter and pressuriser (PFP) unit was found to be effective. This air-cleaning device provides positive-pressure filtered air to the operator in the excavator cabin. Results for monitoring before and after installation of the RESPA®, demonstrated a major

(about four-fold reduction) of RCS in the cabin to a level where respiratory protection is not required. This technology should be tested on the cabins of other plant equipment such as crusher cabins. Installation of these units will be beneficial to the health of mine machinery operators, who operate the equipment from within both fixed and mobile equipment cabins.

Electron microscopy has been carried out to evaluate particle size distribution, and shape, to identify physical characteristics responsible for these particles being entrained in breathing air, and reaching the lung resulting in adverse lung health. Findings from this analysis have challenged the use of EAD to mimic how dust is deposited in the lungs. EAD must include non-spherical particles. Analysis of selected respirable dust samples by electron microscopy has provided insight into the particle size distribution and physical form of the different particle sizes. The greatest number of particles, less than 5μm in in physical diameter, was RCS. The literature notes that this size fraction is more hazardous to lung health. The particle size distribution was shown to be log-normal. The pathogenicity of silica dust is thought to be dependent on particle size, with the most fibrosis causing size of quartz dust particles in lung tissue reported to be 1 – 2 μm (IARC 1987). As most particles identified and measured by SEM had a diameter of 2 - 4 μm in this study (Figure 6.1), adverse effects to lung health will be expected.

Particle shape is also important. The empirical nature of EAD is over-simplified, especially as airborne particles do not exist as perfect spheres. Although density must be considered in converting physical diameter to EAD, findings agree with the literature. Shape will greatly influence how particles penetrate and are deposited into the alveolar region of the lung. Many of the particles are elongated and some are fibrous, rod and needle like.

The use of EAD, that does not match workplace aerosols, nor consider shape, overly simplifies the empirical EAD model and AS2985-2009 sampling efficiency curve. The findings demonstrate that larger length particles have been sampled by cyclone sampler, influencing the particle size distribution

curve. Fibrous, rod-like and elongated particles will be more hazardous due to increased surface area.

The percentage of RCS in respirable dust is important. Graphically the curve is skewed towards the smaller size fraction as % of RCS in respirable dust increases. This suggests that the risk from exposure is not linear. It also demonstrates that both RCS measurement and particle size analysis may be required when proving the efficacy of air cleaning devices such as the RESPA®.

An unexpected finding was the identification of a fibrous particle with morphology similar to erionite. Erionite has a natural fibrous habit and is a mineral silicate that is known to cause mesothelioma when inhaled at high enough concentrations. Further work is required to determine the likelihood of contact with erionite in respirable dust by workers in the Australian mining industry.

8.2 Recommendations

1. Based on the findings of this study, it is highly recommended that the SWA-ES (8-hr, TWA) be lowered from 0.1 mg/m^3 to 0.05 mg/m^3. This will provide a balance between practicabilities of measurement while ensuring that loss of lung function does not fall below the LLN of FEV1 % of predicted at 80%.

2. Given that quartz is pervasive in mines and quarries, assigning a SWA short term exposure limit (STEL) fifteen minute average, for respirable dust (>1 % of RCS in respirable dust) of 0.4 mg/m^3, is also recommended to reduce exposure to RCS and prevent loss of lung function below the LLN. An airborne concentration of 0.4 mg/m^3 can be reliably measured as per AS 2985-2009, for a 15 minute sample and six-place microbalance. The STEL can be used in a complementary way to the proposed SWA-ES for RCS of 0.05 mg/m^3, to identify those tasks with elevated exposure and provide a practical way to rank and reduce RCS exposures, and drive operations to reduce RCS exposure as low as reasonably achievable (ALARA).

3. Health surveillance and personal exposure dust monitoring over time (longitudinally) will add to the weight of evidence that respiratory health is being impacted by over-exposure to RCS. Using FEV1 % of predicted at the LLN of 80% provides a useful screen for further investigation is warranted. This may link RCS exposure with loss of lung function which will provide the impetus for risk reduction. The recently published guidance for occupational health surveillance for those exposed to respirable crystalline silica (HSE 2015) should be used as a guide.

4. Measurement of lung function to ascertain the effects of short-term and cumulative exposure needs to be carried out frequently on individual workers at a range of work stations in mines and quarries to allow early identification of potential health problems.

5. Providing an action against point 4 will require a review of the Australian mine workers health surveillance schemes where there is exposure to airborne crystalline silica.

6. Conducting high resolution CT scans, for workers as a follow up to this Queensland study, may reveal that there are cases of silicosis that have not been previously diagnosed. Further follow-up, including assessment of chest x-rays by trained B readers for the workers in this study should be carried out.

7. A combination of RCS exposure and smoking exacerbates the risk and this must be clearly communicated to workers through appropriate channels. A strategy for increased inspection and compliance enforcement is recommended for those workplaces expected to generate airborne concentrations ≥ 0.04 mg/m^3 RCS such as dimension stone mines.

8. HVAC systems in both mobile and fixed plant in mining are not typically designed to filter out fine particles of respirable dust which can reach the lung when inhaled. These air conditioning systems still allow significant intrusion of RCS into the cabins. The data collected in this study indicates that the RESPA® PFP filter (MERV 16+) may reduce exposures to RCS for operators working in cabins and control rooms on mobile and fixed plant in the mining and quarrying industry. The efficacy of this equipment also needs to be tested on other quarry plant cabins. Preliminary data indicate that installation of these units would be beneficial to the health of machinery operators throughout the mining industry. Notwithstanding, installation of positive pressure air-cleaning devices such as the RESPA® must be compulsory for all cabins of excavator with circular saws cutting dimension stone.

9. The second RESPA® unit installed in this study to clean recirculated air may be size-selectively removing larger particles, and concentrating the smaller silica particles. This observation is important and simply relying on measuring particulate matter inside the cabin is not a good measure of effectiveness. Further testing is required to demonstrate whether installing a second unit for

recirculated air is warranted where residual dust may accumulate inside the cabin which may then subsequently become airborne.

10. Both RCS measurement and particle size analysis should be carried out when proving the efficacy of air cleaning devices such as the RESPA®.

11. With respect to the use of respiratory protective equipment (RPE), all workers should be trained in the correct use of RPE and have fit-tesing in accordance with AS1715-2009 (SA 2009b).

12. An unexpected finding was identification of a fibrous mineral particle with morphology the similar to erionite. Erionite has a natural fibrous habit, is a mineral silicate, and is known to cause mesothelioma when inhaled at high enough concentrations. It is highly recommended that a comprehensive risk characterization and assessment be carried out wherever sites are located in close proximity to zeolite, and where there is potential for exposure to erionite. Confirmation of the presence and extent of erionite by elutriation and high resolution SEM, will assist in determining the extent of health risk to quarry workers in Queensland.

8.3 Further research

1. Further research using spirometry at both group, and individual level, coupled with respiratory questionnaires targeted at high-risk workers will validate correlations between losses of lung function and reported respiratory symptoms. Through a series of trials, the correlation between respiratory symptoms and loss of lung function will be better understood.

   Once validated, the use of respiratory questionnaires to predict loss of lung function can be used as a way to educate workers and to reduce progression of both COPD and silicosis.

2. Comparing the screening of lung function test results in this study with the screening tool provided by NIOSH, which is called SPIROLA® (NIOSH 2014) will further confirm the impact of respiratory health for workers in this study.

   The new version of SPIROLA® (version 3.0.2) was released in 2014.

3. Trialing the use of higher flow samplers with conventional cyclone samplers will set direction in future standard setting. Using higher flow samplers will provide a lower limit of quantitation (LoQ) and improve the accuracy of measurement. The current SWA-ES is limited by sampling methodology and analytical sensitivity. Confirming that higher flow sampling devices conform with ISO 7708, will assist in lowering the current SWA-ES.

4. Follow-up research is recommended using micrographs and elemental scans provided in Chapter 6 to better define, and quantify how particle shape has influenced a deviation from the AS2985-2009 EAD cumulative sampling efficiency curve. No method has been provided by the ISO (2012), to account for particle shape when calculating EAD from physical diameter. Some elongated particles characterised in this study will have a length, diameter and aspect ratio which will be categorized as respirable fibres. The micrographs and particle size distributions from this study can be further evaluated to determine how shape influences the EAD. This can be done by calculating both shape factor and elongation factor, then further evaluating these measures against the theoretical AS2985-2009 sampling efficiency curve which is based on EAD and spherical particles.

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Appendix A

Ethics Approval

Email on behalf of the UWS Human Research Ethics Committee

Dear Sue and Kevin

I'm writing to advise you that the Human Research Ethics Committee has agreed to approve the project.

TITLE: Occupational exposure to respirable crystalline silica – in quarries, small mines and exploration sites Student: Kevin Hedges

Please ensure that the data from this project is kept for the mandatory 5 year period.

The Protocol Number for this project is H6548. Please ensure that this number is quoted in all relevant correspondence and on all information sheets consent forms and other project documentation.

Please note the following:

1) The approval will expire on 30 November 2011. If you require an extension of approval beyond this period, please ensure that you notify the Human Ethics Officer (humanethics@uws.edu.au) prior to this date.

2) Please ensure that you notify the Human Ethics Officer of any future change to the research methodology, recruitment procedure, set of participants or research team.

3) If anything unexpected should occur while carrying out the research, please submit an Adverse Event Form to the Human Ethics Officer. This can be found at http://www.uws.edu.au/research/ors/ethics/human_ethics

4) Once the project has been completed, a report on its ethical aspects must be submitted to the Human Ethics Officer. This can also be found at http://www.uws.edu.au/research/ors/ethics/human_ethics

Finally, please contact the Human Ethics Officer, Kay Buckley on (02) 4736 0883 or at k.buckley@uws.edu.au if you require any further information.

The Committee wishes you well with your research.

Yours sincerely

Dr Janette Perz, Chair, Human Research Ethics Committee

Kay Buckley

Human Ethics Officer, University of Western Sydney

Locked Bag 1797, Penrith Sth DC NSW 1797, Tel: 02 47 360 883

http://www.uws.edu.au/research/ors/ethics/human_ethics

Appendix B Correspondence with Site Senior Executives

School of Natural Sciences
Building M15, Hawkesbury Campus
Locked Bag 1797
PENRITH SOUTH DC NSW 1797
Fax: 02 4570 1383
Email: 97707022@student.uws.edu.au
Phone : 07 4799 7766

Date:
Name
Site Senior Executive
Mine Name
Address 1
Town Qld *Postcode*
Dear *Mr/Ms Name*

Subject: **Participation in research study: *"Occupational exposure to respirable crystalline – in quarries, small mines and exploration sites" H6548.***

Early in 2008 your site completed a Department of Mining and Energy Questionnaire regarding potential exposure of your employees to respirable crystalline silica. In the response to this questionnaire you expressed interest in participating in a University based research study. Your site has been selected as one of the 30 sites to be studied in Queensland. Participation in this study is voluntary. If you are still interested in your site participating in the study, could you please complete the attached consent form and return it me at your convenience. The study will require some of your workers/ contractors being asked to be participants in the study. Once we receive your consent form we will contact you by phone to discuss which workers (job types) are to be monitored and when the monitoring will be undertaken. Participants in the study will be asked to complete a separate consent form which will be provided prior to their participation in the study. It is important that you and the potential participants (site workers) know that there is no obligation to participate in the study. You on behalf of the site, and/or any of the employees who are being monitored can withdraw from the study at any time. If you or any of your employees decide to withdraw, the reason for doing so will remain confidential. Participation in the study will involve your workers (participants) being monitored for personal exposure to respirable dust and respirable crystalline silica and ambient air samples collected for analysis of particulate size fractions. This monitoring should neither inconvenience nor impact a workers (participants) normal work duties. In addition, each of the workers (participants) monitored will be asked to complete a respiratory symptoms questionnaire and undertake a lung function test that will be carried out by one of the research team. The exposure monitoring will be undertaken initially for three days with follow-up monitoring approximately 12 months later. You will be sent a copy of the results of the exposure

monitoring in a de-identified report and each worker (participant) who is monitored will be sent a copy of their individual results. Mining and quarrying workers are potentially exposed to freshly cut quartzite (alpha quartz) in the form of crystalline silica. Exposure to fine particles of airborne quartz, at sufficient concentrations, may result in the operators developing silicosis, a debilitating respiratory condition which may not be diagnosed during their working lifetime. There are approximately 33,000 people employed in the Queensland mining industry and to date there has been no extensive research in Queensland to quantify the levels of exposure to crystalline silica, and therefore the risk of contracting silicosis, using standard air sampling and health assessment methods. In addition to personal exposure monitoring, workers (participants) will be asked to complete a respiratory symptoms questionnaire. A copy is attached for your information. I have provided a copy of the information sheet for employees and worker consent form. I will be contacting you in the near future to organise if and when monitoring can be undertaken. If you have any questions please don't hesitate to contact me on 07 47997 766 or you can also discuss the project with Dr Sue Reed on 02 4570 1492 or by email on s.reed@uws.edu.au.

Yours sincerely

Kevin Hedges

Research Student – University of Western Sydney

Appendix C Site Senior Executive Consent Form

Locked Bag 1797
Penrith South DC NSW 1797 Australia
www.uws.edu.au/researchservices

Human Research Ethics Committee
Office of Research Services
Building K1, Penrith Campus
Tel +61 2 4736 2935 Fax +61 2 4736 2905

University of Western Sydney

Participant Consent Form

This is a project specific consent form. It restricts the use of the data collected to the named project by the named investigators.

Note: if not all of the text in the row is visible please 'click your cursor' anywhere on the page to expand the row. To view guidance on what is required in each section 'hover your cursor' over the bold text.

Project Title: Occupational exposure to respirable crystalline silica in quarries, small mines and exploration sites.

For the Site Senior Executive

I,....., as Site Senior Executive, consent for this site and consenting employees to participate in the research project titled [Occupational exposure to respirable crystalline silica in quarries, small mines and exploration sites].

I acknowledge that:

I have read the participant information sheet [or where appropriate, 'have had read to me'] and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.
The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction. I consent to the workers at this site participate in personal exposure monitoring for respirable crystalline silica and completion of a respiratory questionnaire. I understand that my involvement is confidential and that the information gained during the study may be published but no information about me will be used in any way that reveals my identity. I understand that I or any of the workers can withdraw from the study at any time, without affecting my or the employees relationship with the researcher/s now or in the future. I also acknowledge that the employee or I can withdraw from the study at any time and that the reason for doing so will remain confidential.

Signed:

Name:

Date:

Appendix D Worker (study participant) Consent Form

Locked Bag 1797
Penrith South DC NSW 1797 Australia
www.uws.edu.au/researchservices

Human Research Ethics Committee
Office of Research Services
Building K1, Penrith Campus
Tel +61 2 4736 2935 Fax +61 2 4736 2905

University of Western Sydney

Participant Consent Form

This is a project specific consent form. It restricts the use of the data collected to the named project by the named investigators.

Note: If not all of the text in the row is visible please 'click your cursor' anywhere on the page to expand the row. To view guidance on what is required in each section 'hover your cursor' over the bold text.

Project Title: Occupational exposure to respirable crystalline silica in quarries, small mines and exploration sites - H6548.

I,....., as a worker to be monitored, consent to participate in the research project titled [Occupational exposure to respirable crystalline silica in quarries, small mines and exploration sites].

I acknowledge that:

I have read the participant information sheet [or where appropriate, 'have had read to me'] and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.
The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction. I consent to participate in personal exposure monitoring for respirable crystalline silica, completion of a respiratory questionnaire and breathing tests.

I understand that my involvement is confidential and that the information gained during the study may be published but no information about me will be used in any way that reveals my identity. I understand that I can withdraw from the study at any time without explanation.

Signed:

Name:

Date:

Appendix E Information Sheet

School of Natural Sciences
Building M15, Hawkesbury Campus
Locked Bag 1797
PENRITH SOUTH DC NSW 1797
Fax: 02 4570 1383
Email: 97707022@student.uws.edu.au
Phone : 07 4799 7766

Participant Information Sheet

Project Title:

Occupational exposure to respirable crystalline silica in quarries, small mines and exploration sites – H6548.

Who is carrying out the study?

This study is being carried out by Mr Kevin Hedges (MSc) honours student under the supervision of Dr Sue Reed, Senior Lecturer, School of Natural Resources, University of Western Sydney. The study is being carried out by the Queensland Government, Department of Mines and Energy, in conjunction with the University of Western Sydney.

You are invited to participate in this study conducted as part of a Research Degree under the supervision of Dr. Sue Reed and Prof. Robert Mulley, School of Natural Sciences, University of Western Sydney.

What is the study about?

The aim of the study is to determine current worker inhalation exposure to respirable crystalline silica and determine the relationship between levels of exposure in the work environment and potential for respiratory symptoms such as silicosis.

Mining and quarrying workers are potentially exposed to freshly cut quartzite (alpha quartz) in the form of crystalline silica. Exposure to fine particles of airborne quartz, at sufficient concentrations, may result in the operators developing silicosis, a debilitationg respiratory condition which may not be diagnosed during their working lifetime. There are approximately 33,000 people employed in the Queensland mining industry and to date there has been no extensive research in Queensland to quantify the levels of exposure to crystalline silica, and therefore the risk of contracting silicosis, using standard air sampling and health assessment methods.

What does the study involve?

Your work site has been selected as one of the sites to be studied in Queensland. Participation in the study will involve the workers at each work site being monitored for personal exposure to respirable dust and respirable crystalline silica. Ambient air samples will also be collected for analysis of particulate size fractions. Respiratory symptoms questionnaires and lung function tests (spirometry) will also be coordinated at the same time.

The monitoring will be undertaken initially for three days with follow-up monitoring approximately 12 months later. You will be sent a copy of your individual results and site management will be sent a copy of the consolidated results in a de-identified report. The information provided will assist industry improve dust control and protect worker health.

To enable the personal exposures to respirable dust and crystalline silica you are being asked to wear a sampling pump with sampling head (cyclone) to collect the very fine dust that you may be exposed to during a full work shift. The personal air sampling will be carried out in accordance with AS 2985-2004 Workplace atmospheres – Method for sampling and gravimetric determination of respirable dust. The samples collected will be analysed for both mass of respirable dust and silica content.

The personal exposure sampling equipment should not impact your normal work. If you experience any problems or inconvenience from the equipment please notify the researcher.

In addition, we would like you to complete a respiratory symptoms questionnaire and to undertake a lung function test (spirometry) to determine whether you have any symptoms that may be caused from dust exposure. If the questions are not clear or you need assistance the researcher will assist.

How much time will the study take?

The research project and all monitoring will be completed in June 2011.

Will the study benefit me?

The study will be of benefit in that personal exposure monitoring will be carried out to assess your exposure to respirable crystalline silica. You will be provided with a copy of both your respirable dust exposure results and your lung function results for your own records.

Will the study involve any discomfort to me?

You will be asked to wear a personal monitoring pump and sampling head which is small and lightweight. This sampling apparatus should neither effect, nor convenience your normal work. The lung function test unit (spirometer) will require that you breathe into a tube. It will determine how quickly your lung can be emptied and filled and how much air can be blown out. You will probably be familiar with the test as it is included in most medical check-ups. The respiratory questionnaire and breathing test should take no longer than 45 minutes.

How is the study paid for?

The study is being sponsored by the Department of Mines and Energy. The project is being carried out for research and to benefit the Mining Industry. There is no conflict of interest.

Will anyone else know the results? How will the results be disseminated?

The Site Senior Executive of your site will be notified of all results related to the site. Apart from the investigators no other person will have access to the individual results, except as required by law. All results will be de-identified. In other words a report of the study may be submitted for publication, but individual participants or sites will not be identified in such a report. All participants will receive information about the findings of the research.

Can I withdraw from the study?

Participation is entirely voluntary. You are not obliged to be involved and if you do participate you can withdraw at any time without giving any reason and without any consequences. By completing and providing the attached respiratory questionnaire this demonstrates that you provide consent for this information to be used as research. Refusal to participate or withdraw from the research will not prejudice the participant's future care, employment or academic progress in any way. As the data will remain anonymous, once the data is submitted participants cannot be guaranteed the right to withdraw their data at any time.

Can I tell other people about the study?

Yes you can tell other people about the study by providing them with the chief investigator's contact details. They can contact the chief investigator to discuss their participation in the research project and to obtain an information sheet.

What if I require further information?

When you have read this information, Dr. Sue Reed or Mr Kevin Hedges will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact the Principal Researchers, Dr. Sue Reed (phone 02 4570 1492), Mr. Kevin Hedges (phone 07 4799 7766) at any time.

What if I have a complaint?

This study has been approved by the University of Western Sydney Human Research Ethics Committee. The approval number is H5648. If you have any complaints or reservations about the ethical conduct of this research you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0083, Fax 02 4736 0013 or email humanethics@uws.edu.au. Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

If you agree to participate in this study, you will be asked to sign the Participant Consent Form.

Appendix F Study Respiratory Questionnaire

Respiratory Questionnaire

Questionnaire based on the MRC (UK) Respiratory Questionnaire 1986,

RESPIRATORY SYMPTOMS SURVEY

Respiratory Questionnaire

Questionnaire based on the MRC (UK) Respiratory Questionnaire 1986, which has been extensively validated. This questionnaire is intended to be completed by an interviewer rather than by the patient. Additional questions have been added to cover clinical aspects of bronchial hyper responsiveness validated by the Department of Occupational and Environmental Medicine, National Lung Institute,

The British Occupational Health Research Foundation (BOHRF) concluded that in the clinical setting questionnaires that identify symptoms of wheeze and/or shortness of breath which improve on days away from work or on holidays have a high sensitivity, but relatively low specificity for occupational asthma.

Preamble

I am going to ask some questions, mainly about your respiratory symptoms. I would like you to answer **Yes** or **No** whenever possible.

If the subject is disabled from walking from any condition other than heart and lung disease, please begin questionnaire at **Question 5** and mark the adjacent box ☐

Participant Number……

Breathlessness and Wheezing

During the last month:

1. Are you troubled by shortness of breath when hurrying on level ground or walking up a slight hill? Yes ☐ No ☐

2. Do you get short of breath walking with other people of your age on level ground? Yes ☐ No ☐

3. Do you have to stop for breath when walking at your own pace on level ground?

Yes ☐ No ☐

4. If you run, or climb stairs fast do you ever

a. cough? Yes ☐ No ☐

b. wheeze? Yes ☐ No ☐

c. get tight in the chest? Yes ☐ No ☐

5. Is your sleep ever broken

a. by wheeze? Yes ☐ No ☐

b. difficulty in breathing? Yes ☐ No ☐

6. Do you ever wake up in the morning (or from your sleep if a shift worker)

a. with wheeze? Yes ☐ No ☐

b. difficulty with breathing? Yes ☐ No ☐

7. Do you ever wheeze?

a. if you are in a smoky room? Yes ☐ No ☐

b. if you are in a very dusty place? Yes ☐ No ☐

8. If you have answered yes to Q5, Q6 or Q7, are your symptoms better

a. at weekends (or equivalent if shift worker)? Yes ☐ No ☐

b. when you are on holidays? Yes ☐ No ☐

If **Yes** to **Question 8**, please record details of any occupational exposure to respiratory hazards eg isocyanates, wood dust, or formaldehyde.

Cough

9. Do you usually cough first thing in the morning in winter?

Yes ☐ No ☐

10. Do you usually cough during the day – or at night – in the winter?

Yes ☐ No ☐

11. If you have answered yes to Q9 or Q10, do you cough like this on most days for as much as three months each year? Yes ☐

No ☐

Phlegm

12. Do you usually bring up phlegm from your chest first thing in the morning in winter? Yes ☐ No ☐

13. Do you usually bring up any phlegm from your chest during the day – or at night – in winter? Yes ☐ No ☐

14. If you have answered yes to Q12 or Q13, do you bring up phlegm like this on most days for as much as three months each year? Yes ☐

No ☐

Periods of cough and phlegm

15. In the past three years, have you had a period of (increased) cough and phlegm lasting for three weeks or more? Yes ☐

No ☐

Q16. If you have answered yes to Q15, have you had more than one such episode?

Yes ☐ No ☐

Chest Illnesses

17. During the past three years, have you had any chest illness that has kept you from your usual activities for as much as a week? Yes ☐

No ☐

18. If you have answered yes to Q17, Did you bring up more phlegm than usual in any of these illnesses? Yes ☐

No ☐

19. If you have answered yes to Q18, Have you had more than one illness like this in the past three years? Yes ☐ No ☐

Past Illnesses

20. Have you ever had, or been told that you have had:

a. An injury, or operation affecting your chest? Yes ☐ No ☐

b. Heart trouble? Yes ☐ No ☐

c. Bronchitis? Yes ☐ No ☐

d. Pneumonia Yes ☐ No ☐

e. Pleurisy? Yes ☐ No ☐

f. Asthma? Yes ☐ No ☐

g. Other chest trouble? Yes ☐ No ☐

h. Hay fever? Yes ☐ No ☐

Tobacco Smoking

21. Do you smoke? Yes ☐ No ☐

Q22. If you answered no to Q21, have you ever smoked as much as one

Cigarette a day for as long as one year? Yes ☐ No ☐

If **No** to **Question 21 or 22**, omit remaining questions on smoking.

23. How old were you when you started smoking regularly?

_____

24a. Do (did) you smoke manufactured cigarettes? Yes ☐ No ☐

If you answered yes to Q24a,

How many do you (did) you usually smoke per day? _____

Q24b. on weekdays? _____

Q24c. at weekends? _____

25. Do you smoke any other forms of tobacco? Yes ☐ No ☐

If Yes to Q25 : Record details under Additional Notes

For ex-smokers

Q26. When did you give up smoking altogether? Month _____Year _____

Additional Notes

Appendix G Example (Excavator & Saw Operator) Completed Respiratory Questionnaire

RESPIRATORY SYMPTOMS SURVEY

Respiratory Questionnaire

Questionnaire based on the MRC (UK) Respiratory Questionnaire 1986, which has been extensively validated. This questionnaire is intended to be completed by an interviewer rather than by the patient. Additional questions have been added to cover clinical aspects of bronchial hyper responsiveness validated by the Department of Occupational and Environmental Medicine, National Lung Institute.
The British Occupational Health Research Foundation (BOHRF) concluded that in the clinical setting questionnaires that identify symptoms of wheeze and/or shortness of breath which improve on days away from work or on holidays have a high sensitivity, but relatively low specificity for occupational asthma.

Preamble

I am going to ask some questions, mainly about your respiratory symptoms. I would like you to answer **Yes** or **No** whenever possible.

If the subject is disabled from walking from any condition other than heart and lung disease, please begin questionnaire at **Question 5** and mark the adjacent box ☐

Participant Number: A3

Breathlessness and Wheezing

During the last month :

1. Are you troubled by shortness of breath when hurrying on level ground or walking up a slight hill? Yes ☐ No ☑
2. Do you get short of breath walking with other people of your age on level ground? Yes ☐ No ☑
3. Do you have to stop for breath when walking at your own pace on level ground? Yes ☐ No ☑
4. If you run, or climb stairs fast do you ever
   a. cough? Yes ☐ No ☑
   b. wheeze? Yes ☐ No ☑
   c. get tight in the chest? Yes ☐ No ☑
5. Is your sleep ever broken
   a. by wheeze? Yes ☑ No ☐
   b. difficulty in breathing? Yes ☐ No ☑
6. Do you ever wake up in the morning (or from your sleep if a shift worker)
   a. with wheeze? Yes ☑ No ☐
   b. difficulty with breathing? Yes ☐ No ☑

A3

7. Do you ever wheeze

a. if you are in a smoky room? Yes ☐ No ☑

b. if you are in a very dusty place? Yes ☐ No ☑

8. **If you have answered yes to Q5, Q6 or Q7**, are your symptoms better

a. at weekends (or equivalent if shift worker)? Yes ☐ No ☑

b. when you are on holidays? Yes ☐ No ☑

If **Yes** to **Question 8**, please record details of any occupational exposure to respiratory hazards eg isocyanates, wood dust, or formaldehyde.

(2years) 25 Quarrying (Alloy) including 18 years as Shot Man
7 years (Sandstone) (See Back for Additional)

Cough

9. Do you usually cough first thing in the morning in winter? Yes ☐ No ☑

10. Do you usually cough during the day – or at night – in the winter? Yes ☐ No ☑

11. **If you have answered yes to Q9 or Q10**, do you cough like this on most days for as much as three months each year? Yes ☐ No ☐

Phlegm

12. Do you usually bring up phlegm from your chest first thing in the morning in winter? Yes ☑ No ☐

13. Do you usually bring up any phlegm from your chest during the day – or at night – in winter? Yes ☑ No ☐

14. **If you have answered yes to Q12 or Q13**, do you bring up phlegm like this on most days for as much as three months each year? Yes ☑ No ☐

Periods of cough and phlegm

15. In the past three years, have you had a period of (increased) cough and phlegm lasting for three weeks or more? Yes ☑ No ☐

Q16. **If you have answered yes to Q15**, have you had more than one such episode? Yes ☐ No ☐

A3

Chest Illnesses

17. During the past three years, have you had any chest illness that has kept you from your usual activities for as much as a week? Yes ☐ No ☑

18. **If you have answered yes to Q17**, Did you bring up more phlegm than usual in any of these illnesses? Yes ☐ No ☐

19. **If you have answered yes to Q18**, Have you had more than one illness like this in the past three years? Yes ☐ No ☐

Past Illnesses

20. Have you ever had, or been told that you have had:

a. An injury, or operation affecting your chest? Yes ☐ No ☑

b. Heart trouble? Yes ☐ No ☑

c. Bronchitis? Yes ☐ No ☑

d. Pneumonia Yes ☑ No ☐

e. Pleurisy? Yes ☐ No ☑

f. Asthma? Yes ☑ No ☐

g. Other chest trouble? Yes ☐ No ☑

h. Hay fever? Yes ☑ No ☐

Tobacco Smoking

21. Do you smoke? Yes ☑ No ☐

Q22. **If you answered no to Q21**, have you ever smoked as much as one cigarette a day for as long as one year? Yes ☑ No ☐

If **No** to **Question 21 or 22, omit** remaining questions on smoking.

23. How old were you when you started smoking regularly? 18.

24a. Do (did) you smoke manufactured cigarettes? Yes ☑ No ☐

If you answered yes to Q24a,

How many do you (did) you usually smoke per day? 20-30

Q24b. on weekdays? 20-30

Q24c. at weekends? 40

A3

25. Do you smoke any other forms of tobacco? Yes ☑ No ☐

If Yes to Q25 : Record details under Additional Notes

For ex-smokers

Q26. When did you give up smoking altogether? Month _____ Year _____

Additional Notes

Recent

- Diagnosed with Asthma but does not have medication for this. Book in Dr Ultrasound in May. 2009. after

Self presented to doctor due to [redacted] in right hand side of Chest. (Patient suspects may be peptic ulcer)

Had a Chest XRay 2 months ago came back Ok.

Work History

25 years in Quarrying + Stone Masonry industry.

- 2 years at [redacted] (Heating + carry coals)
- 18 years as stone mason at [redacted] quarries.
- 7 years in Sandstone quarries

At [redacted] Rib Loads trucks approximately 5-6 times/week at 30mins - 45mins/load

The remainder of time in quarries raw.

Appendix H Respiratory questionnaire % responses against each question.

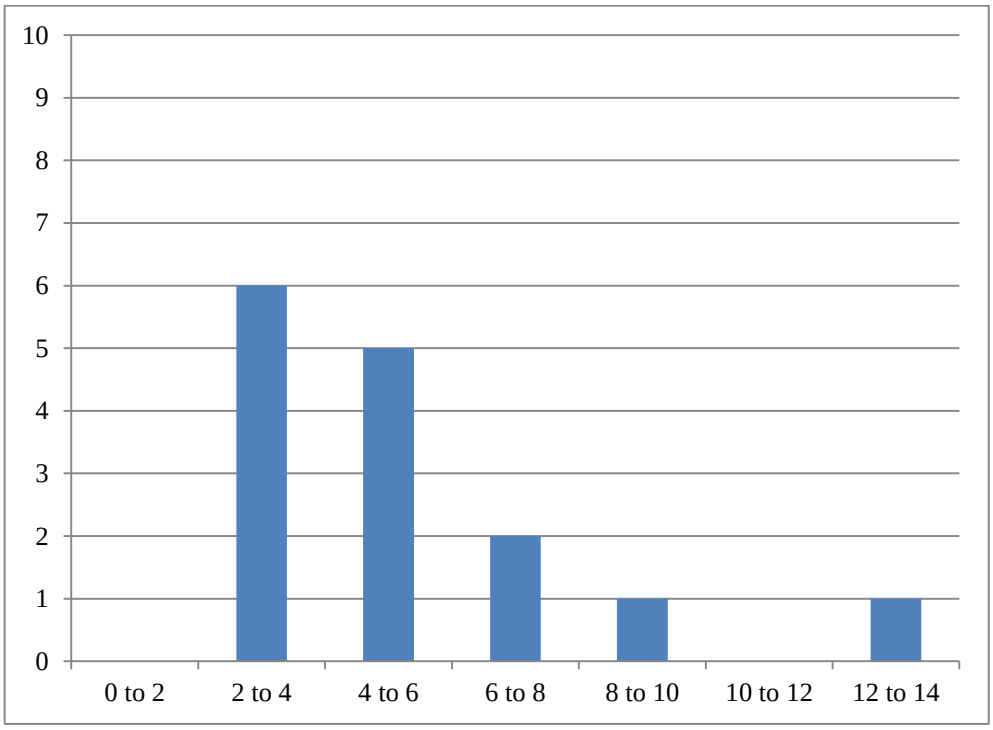
Question #	Question	%
Breathlessness and wheezing		
1	Are you troubled by shortness of breath when hurrying on level ground or walking up a slight hill?	**27**
2	Do you get short of breath walking with other people of your age on level ground?	**10**
3	Do you have to stop for breath when walking at your own pace on level ground?	**0**
4	If you run, or climb stairs fast do you ever:	
a	Cough?	**37**
b	Wheeze?	**27**
c	Get tight in the chest?	**13**
5	Is your sleep ever broken:	
a	By wheeze?	**13**
b	By difficulty in breathing?	**10**
6	Do you ever wake up in the morning (or from your sleep if a shift worker):	
a	By wheeze?	**20**
b	By difficulty in breathing?	**7**
7	Do you ever wheeze?	
a	If you are in a smoky room?	**7**
b	If you are in a very dusty place?	**23**
8	If you have answered yes to Q5, Q6 or Q7, are your symptoms better:	
a	At weekends (or equivalent if shift worker)?	**17**
b	When you are on holidays?	**10**
Cough		
9	Do you usually cough first thing in the morning in winter?	**33**
10	Do you usually cough during the day – or at night – in the winter?	**30**
11	**If you have answered yes to Q9 or Q10**, do you cough like this on most days for as much as three months each year?	**17**
Phlegm		
12	Do you usually bring up phlegm from your chest first thing in the morning in winter?	**27**
13	Do you usually bring up any phlegm from your chest during the day – or at night – in winter?	**33**
14	**If you have answered yes to Q12 or Q13**, do you bring up phlegm like this on most days for as much as three months each year?	**20**
Periods of cough and phlegm		
15	In the past three years, have you had a period of (increased) cough and phlegm lasting for three weeks or more?	**17**
16	If you have answered yes to Q15, have you had more than one such episode?	**10**
Chest Illnesses		
17	During the past three years, have you had any chest illness that has kept you from your usual activities for as much as a week?	**13**
18	**If you have answered yes to Q17**, Did you bring up more phlegm than usual in any of these illnesses?	**7**
19	**If you have answered yes to Q18**, Have you had more than one illness like this in the past three years?	**3**
Question #	**Question**	**%**

Past Illnesses		
20	Have you ever had, or been told that you have had:	
a	An injury or operation affecting your chest?	**7**
b	Heart trouble?	**7**
c	Bronchitis?	**3**
d	Pneumonia?	**13**
e	Pleurisy?	**3**
f	Asthma?	**43**
g	Other chest trouble?	**7**
h	Hay fever?	**30**
Tobacco Smoking		
21	Do you smoke?	**73**
22	**If you answered no to Q21**, have you ever smoked as much as one cigarette a day for as long as one year?	**70**
	If **No** to **Question 21 or 22**, omit remaining questions on smoking.	
23	How old were you when you started smoking regularly?	
24a	Do (did) you smoke manufactured cigarettes?	**57**
	If you answered yes to Q24a, how many do you (did) you usually smoke per day?	
a	On weekdays?	
b	At weekends?	
25	Do you smoke any other forms of tobacco?	**10**

Appendix I Elemental scans, particle size distributions, micrographs and spectrums for individual samples.

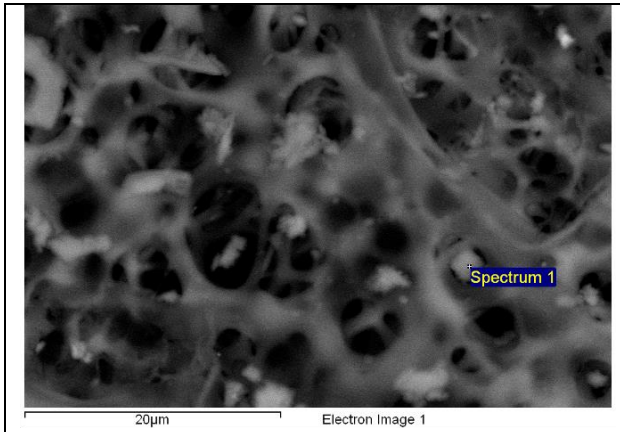
Appendix I1 Elemental scan for F5137

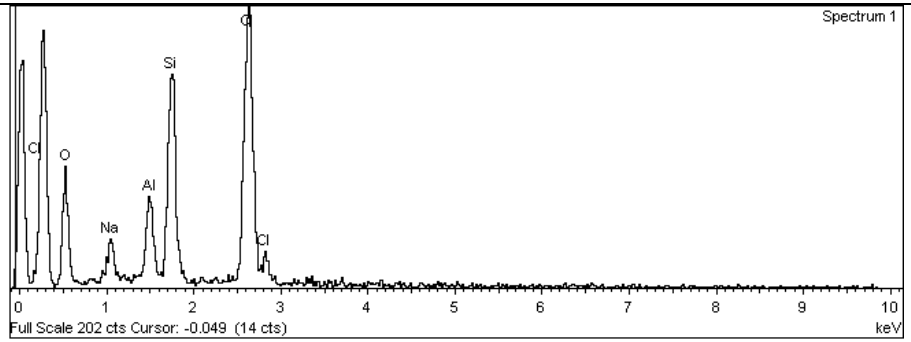
Particle #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	1/1	2.2	O, Si	Al, Na
2	2/1	7.3	O, Si	Al, K, Fe
3	4/1	3.9	O, Si	-
4	5/1	4.2	O, Si	-
5	6/1	2.7	O, Si	Al, K
6	7/1	6.7	O, Si	Al, K
7	8/1	9.1	O, Si	Al, K
8	8/2	12.3	S, Fe	-
9	8/3	4.4	O, Si	-
10	9/1	3.3	O, Si	-
11	10/1	4.8	O, Fe	Si, Al
12	11/1	5.4	O, Si	Al, K, Fe
13	13/1	2.4	O, Si	Al, K
14	14/1	4.9	O, Si	Al, K, Fe
15	15/1	3.6	O, Si	Al



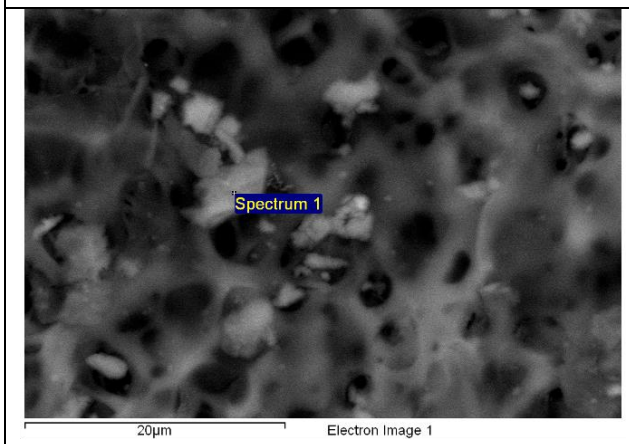
Appendix I2: Particle size distribution for F5137

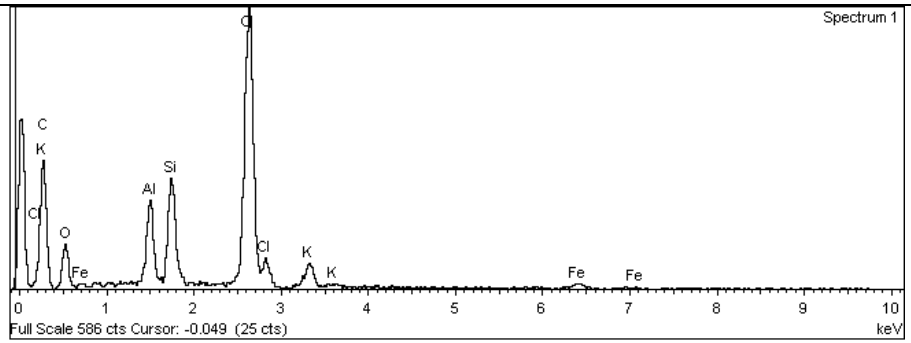
F5137





Particle 1





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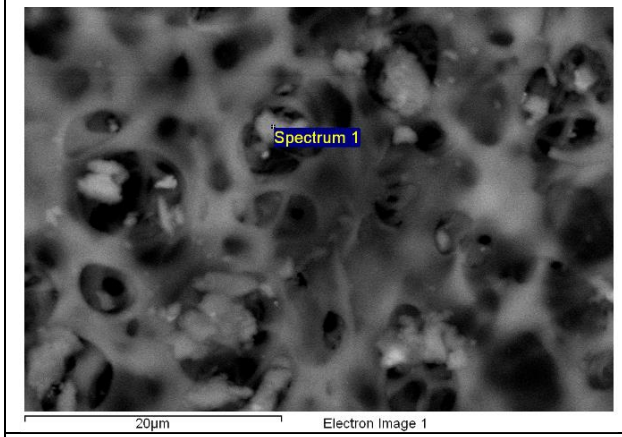

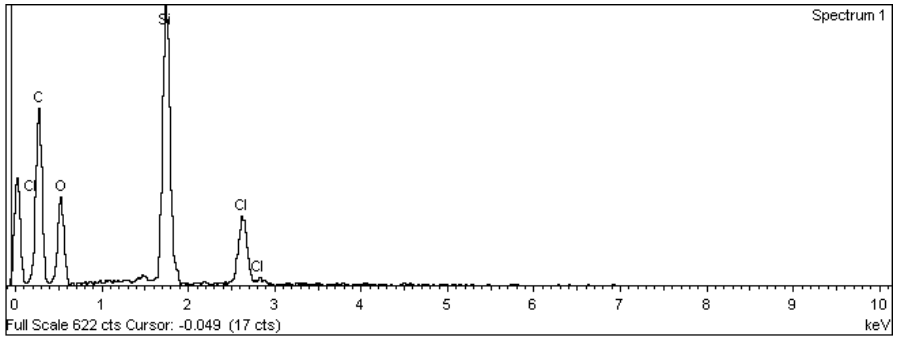

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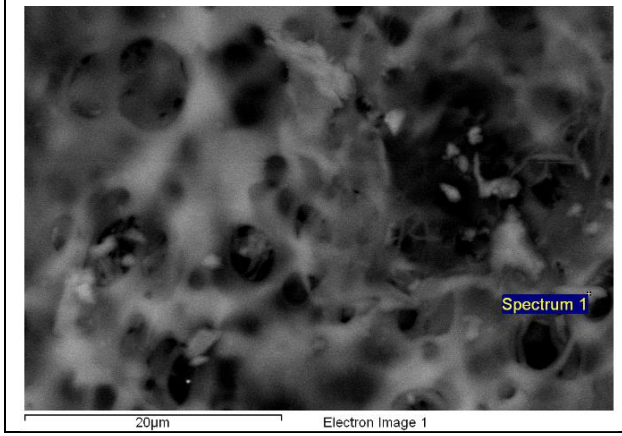

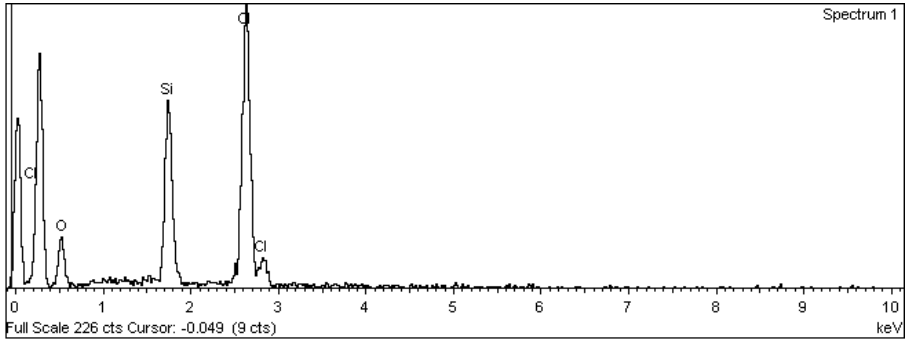

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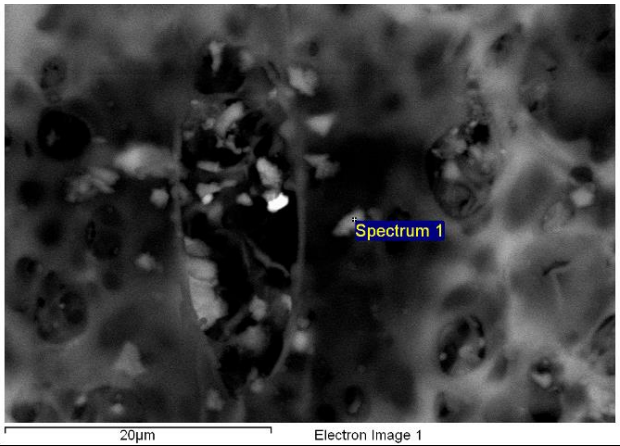

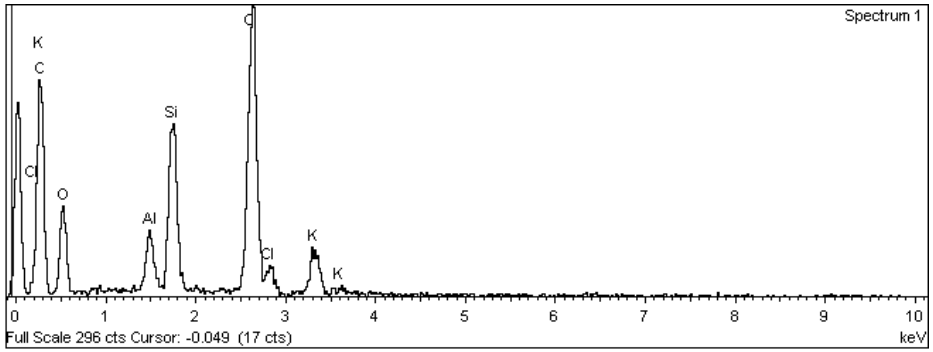

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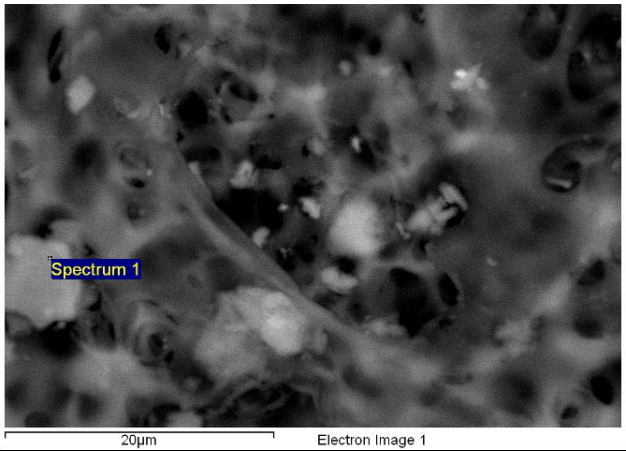

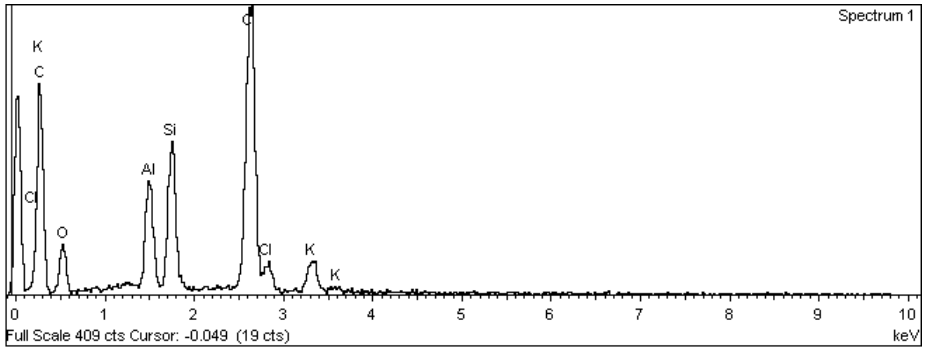

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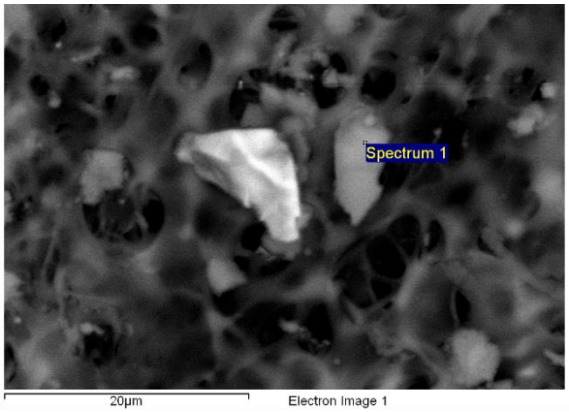
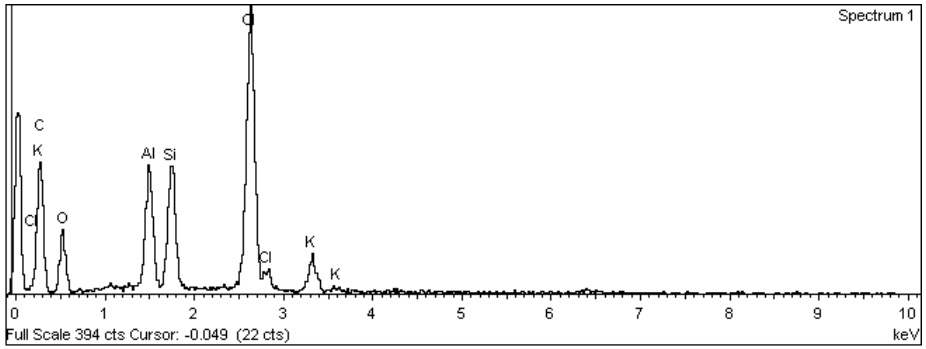
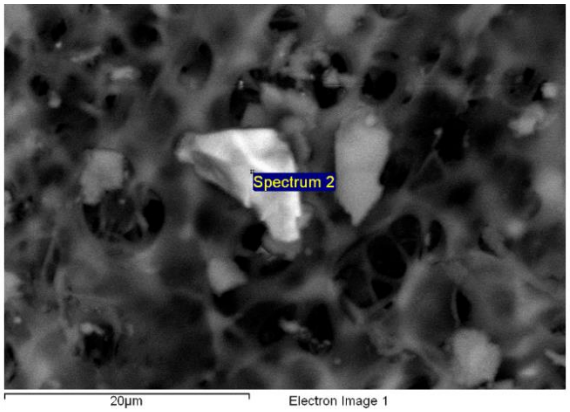
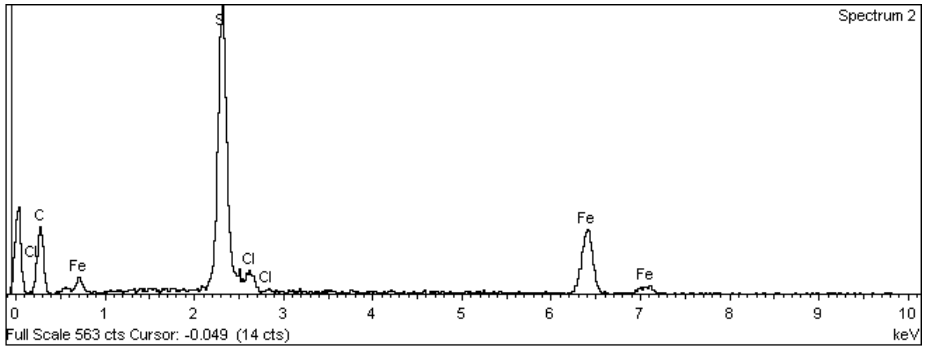




Particle 7





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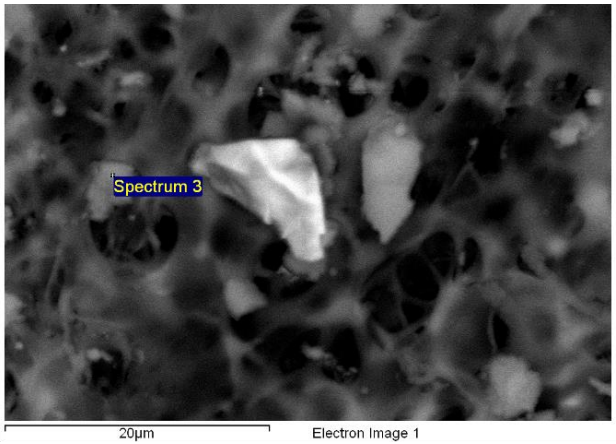

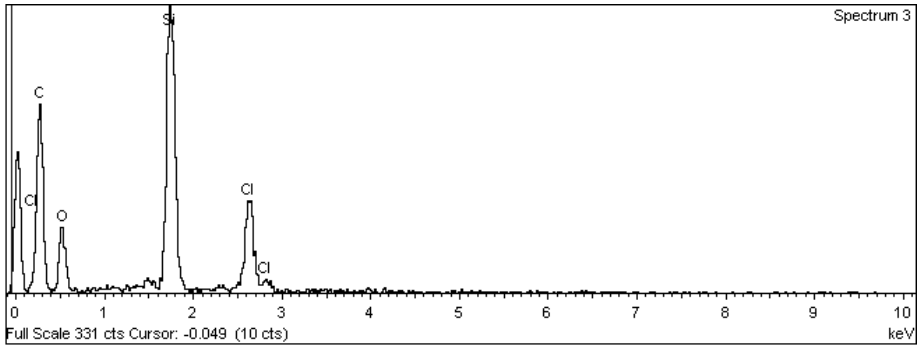

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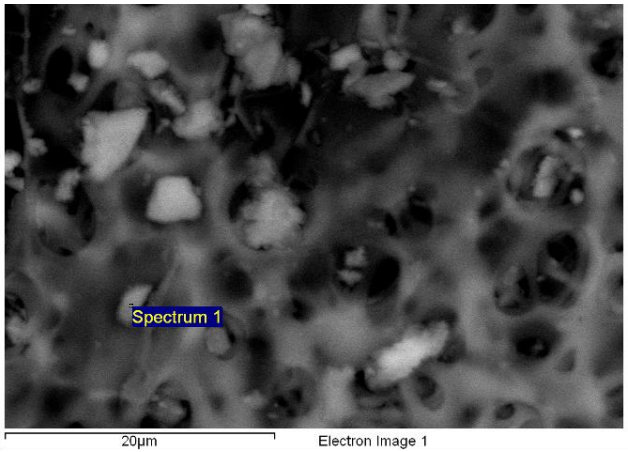

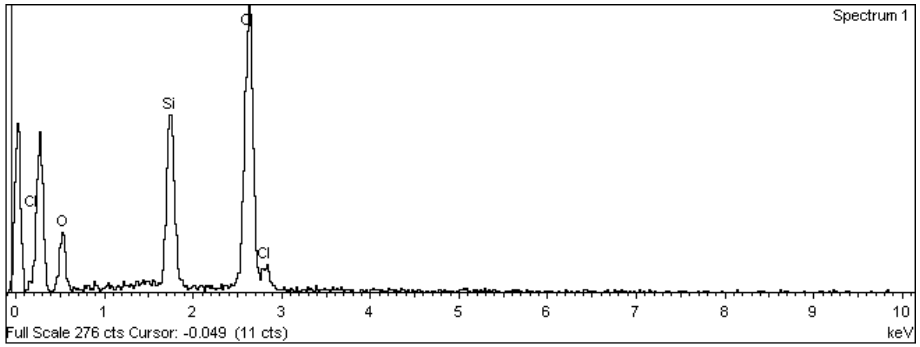

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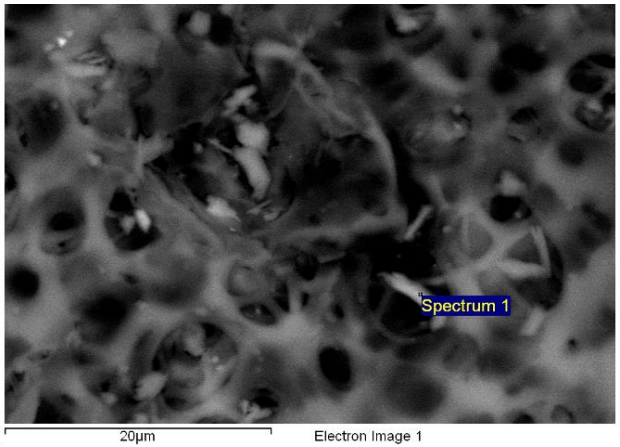

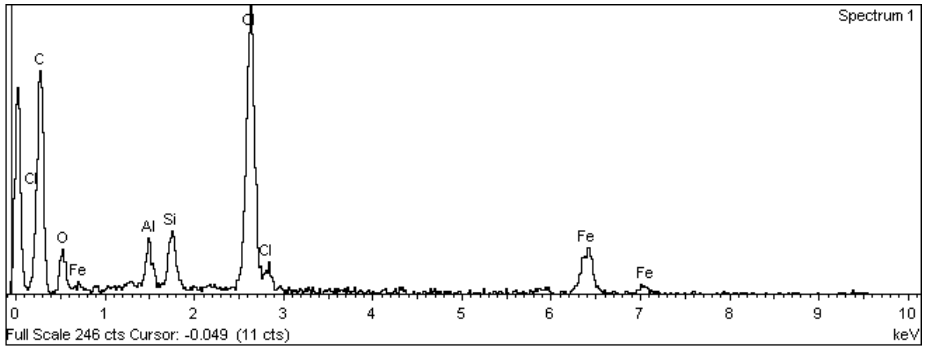

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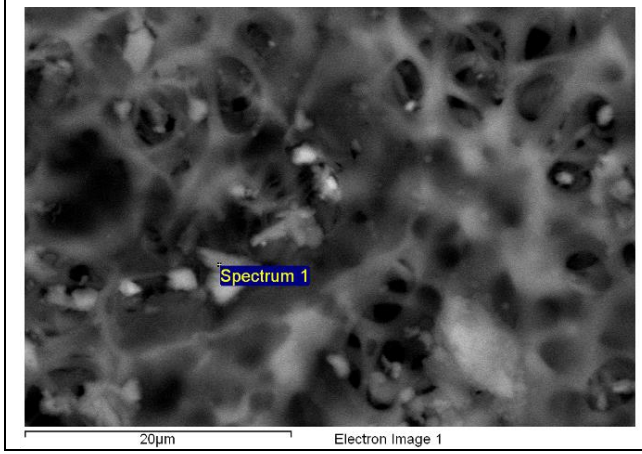

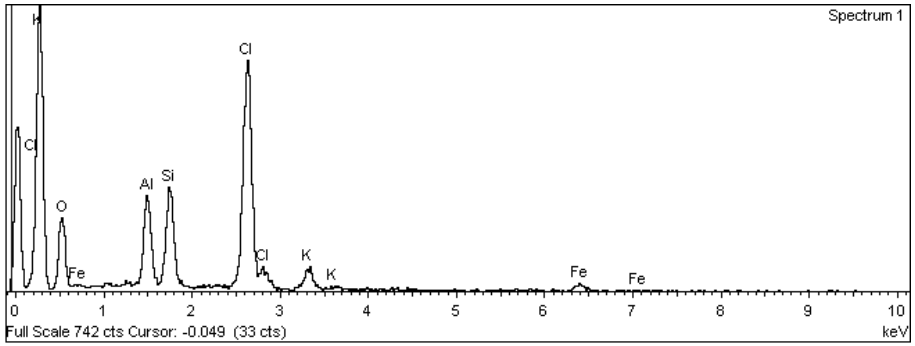

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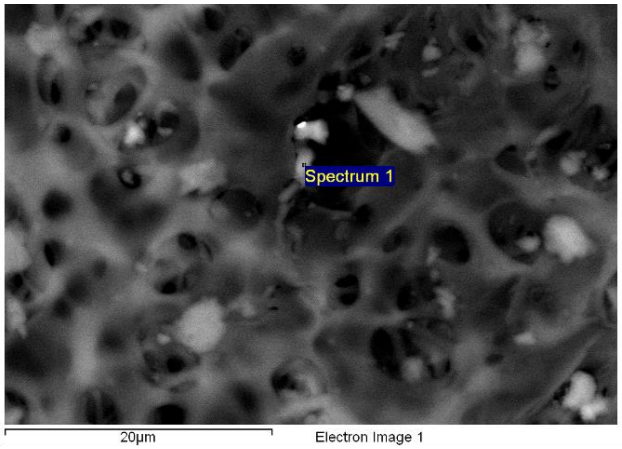
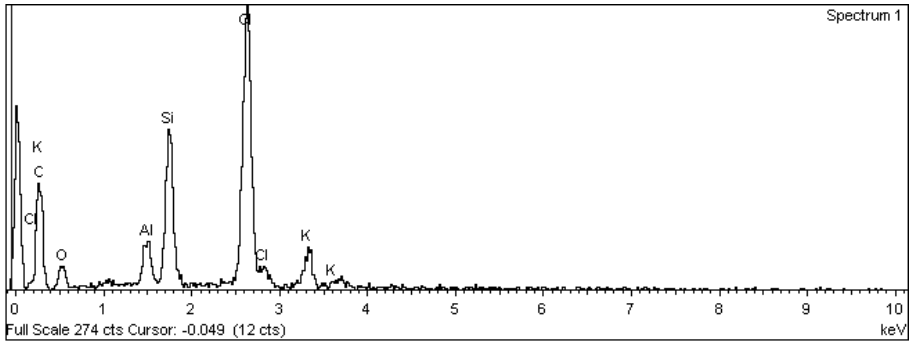
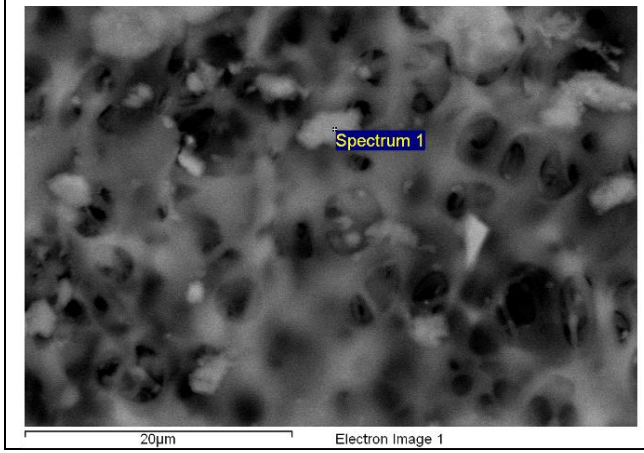
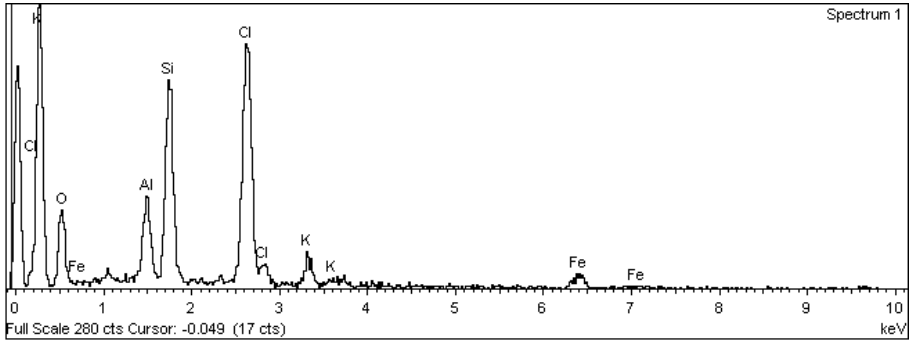


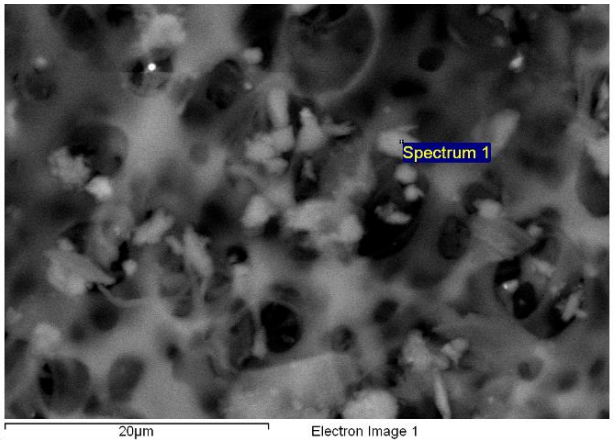


Particle 13

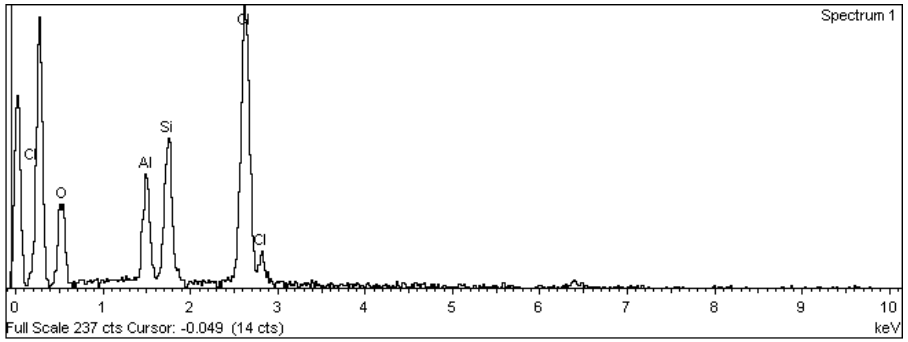




Particle 14



I3 EM micrograph images for F5137



Particle 15

I4 Elemental spectrums for F5137

I5 Elemental scan for F5007

Particle #	Image/Field #	Diameter (μm)	Major Elements	Minor Elements
1	1/1	4.4	O, Si	Al, K, Fe, S
2	1/2	5.1	O, Si	Al, K, Fe, S
3	2/2	7.6	O, Si	Fe, Al, S, Bi
4	2/3	3.4	O, Si	Al, Fe
5	3/1	4.0	O, Si	Al, K
6	4/1	8.5	O, Si	Al, K, Fe
7	4/2	3.6	O, Fe	Si, Al, Ca, Mn
8	5/1	4.3	O, Fe	Si, Al
9	5/2	2.7	O, Si	Al, K, Na
10	6/1	4.6	O, Si	Al
11	7/1	6.3	O, Si, Al	K, Fe
12	8/1	2.6	O, Si	Al, K, Na, Fe
13	9/1	3.9	O, Cu, S	Si, Al, Fe
14	9/2	4.7	O, Si	Fe, Al, K
15	12/1	3.1	O, Si	Al, K

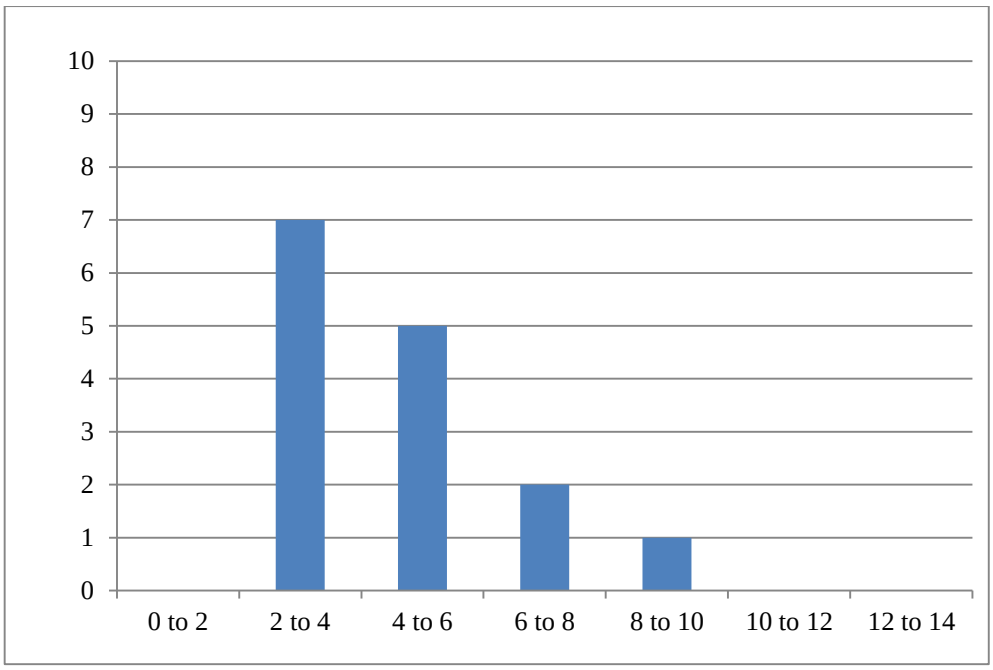
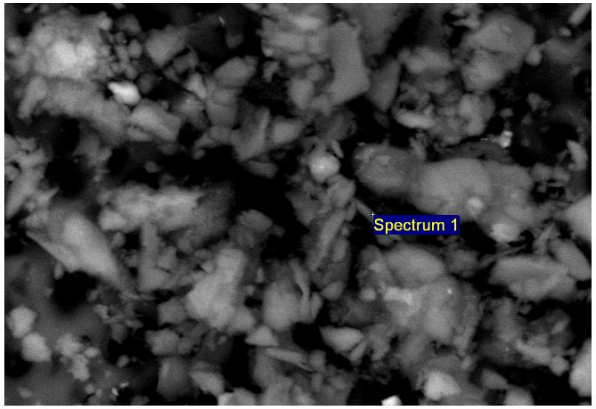
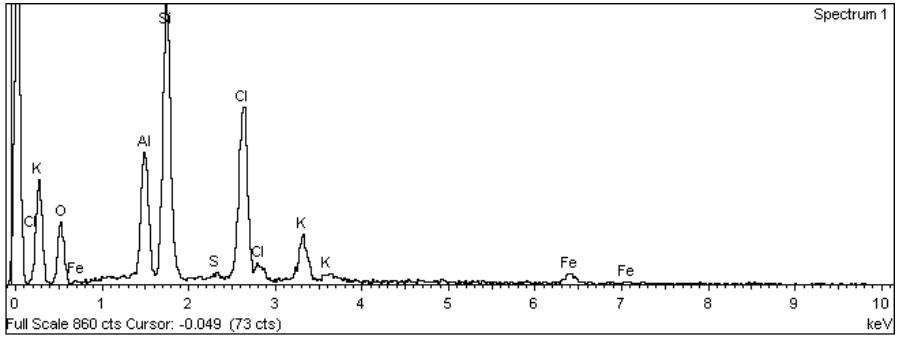
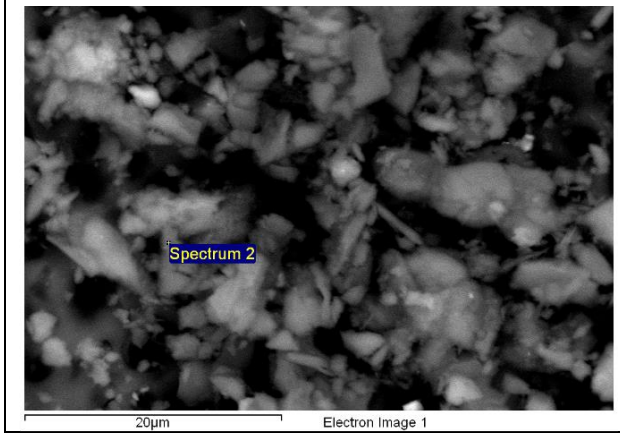


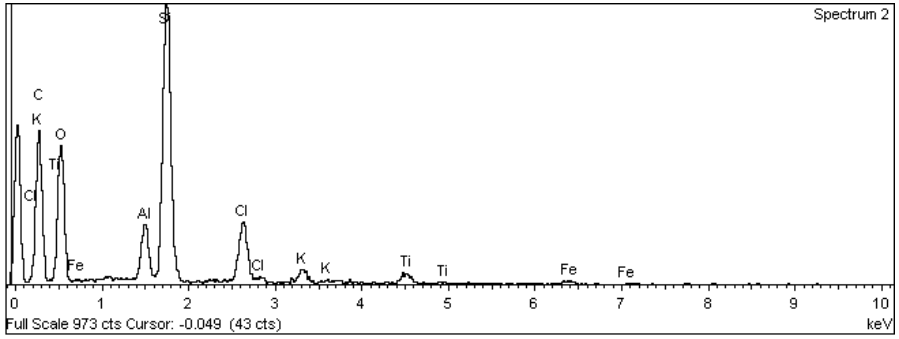
Figure I6: Particle size distribution for F5007

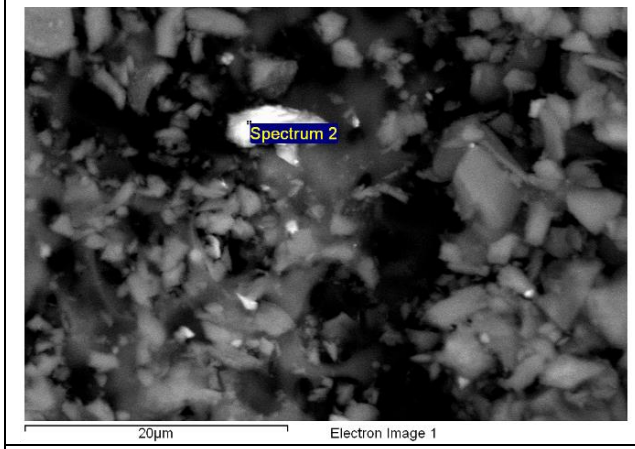
F5007

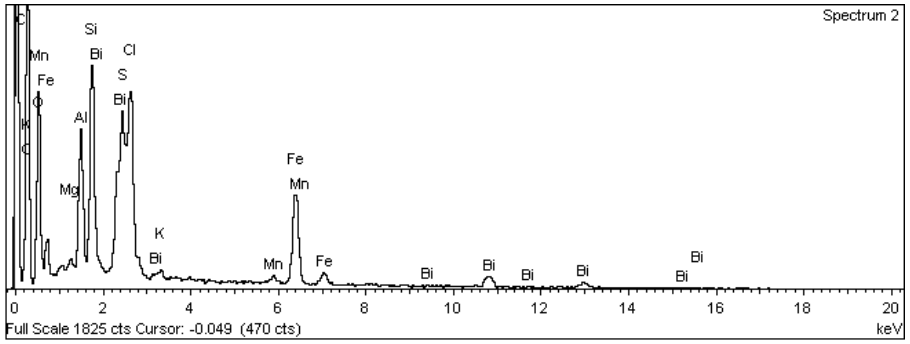

Spectrum 1
20µm
Electron Image 1

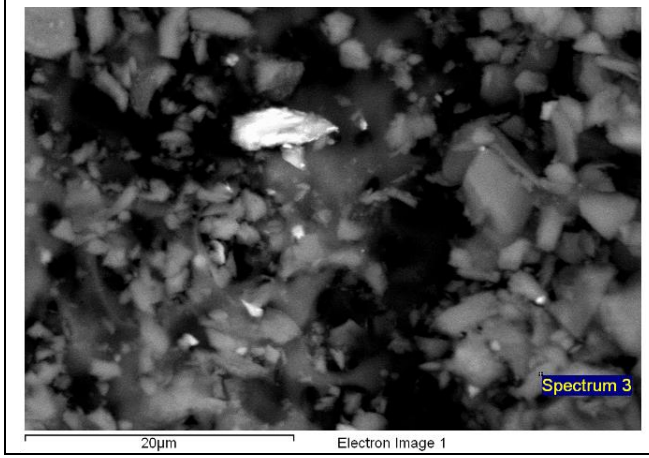

Spectrum 1
Si
Cl
Al
K
Cl
O
Fe
S
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 860 cts Cursor: -0.049 (73 cts)
keV

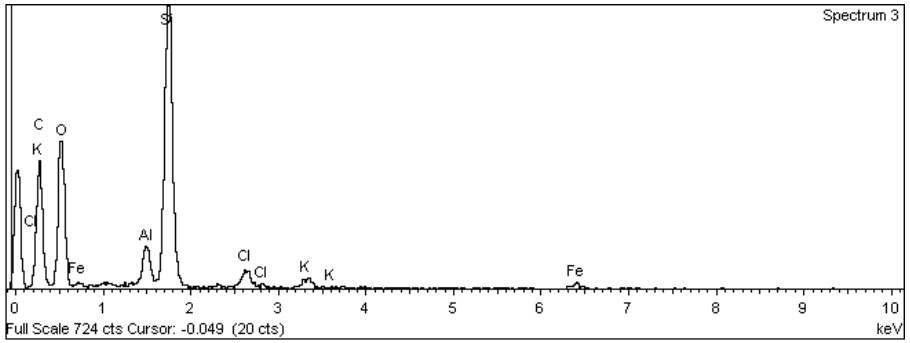

Spectrum 2
20µm
Electron Image 1

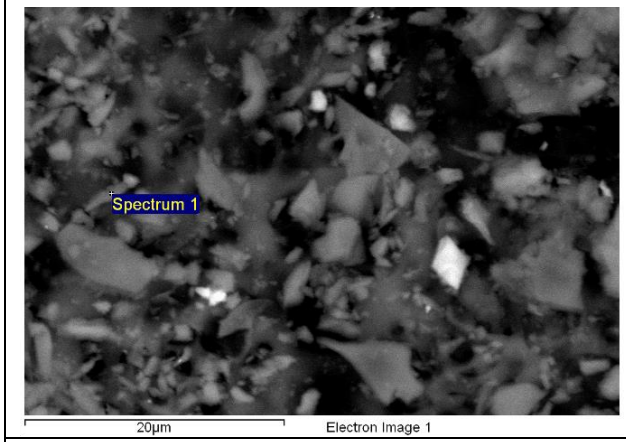

Spectrum 2
Si
C
K
O
Ti
Cl
Al
Cl
Fe
Cl
K
K
Ti
Ti
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 973 cts Cursor: -0.049 (43 cts)
keV

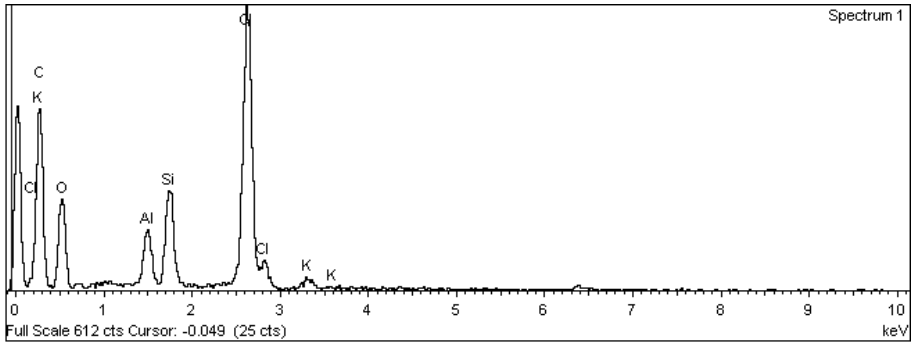

Spectrum 2
20µm
Electron Image 1

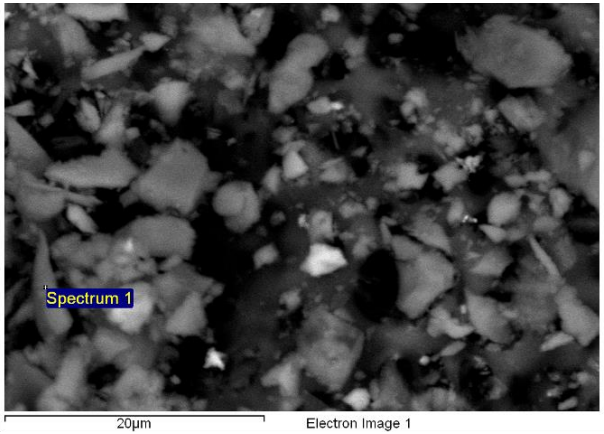

Spectrum 2
C
Mn
Fe
O
K
Cl
Si
Bi
Cl
S
Bi
Al
Mg
K
Bi
Fe
Mn
Mn
Fe
Bi
Bi
Bi
Bi
Bi
Bi
0 2 4 6 8 10 12 14 16 18 20
Full Scale 1825 cts Cursor: -0.049 (470 cts)
keV

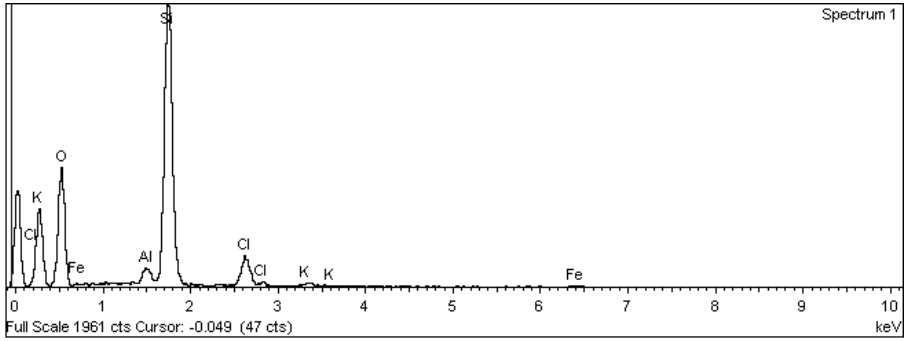

Spectrum 3
20µm
Electron Image 1

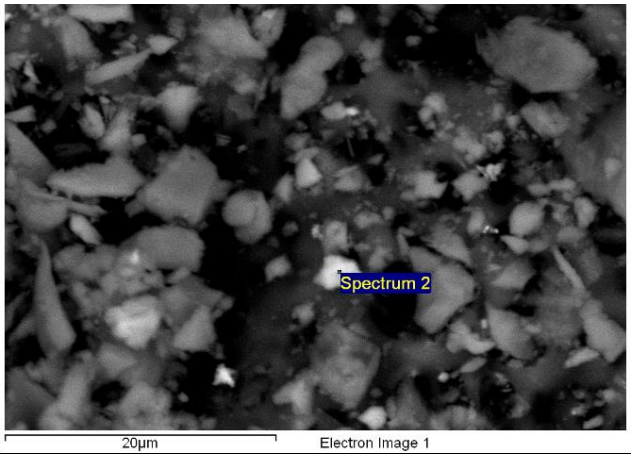

Spectrum 3
Si
C
K
O
Cl
Fe
Al
Cl
Cl
K
K
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 724 cts Cursor: -0.049 (20 cts)
keV

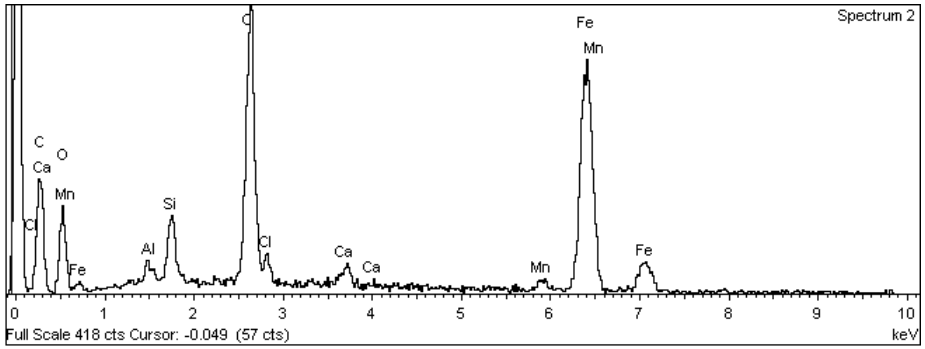

Spectrum 1
20µm
Electron Image 1

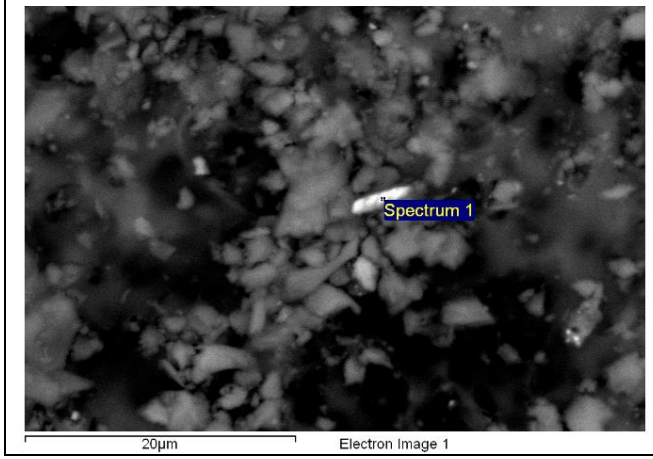

Spectrum 1
C
K
Cl
O
Al
Si
Cl
Cl
K
K
0
1
2
3
4
5
6
7
8
9
10
Full Scale 612 cts Cursor: -0.049 (25 cts)
keV

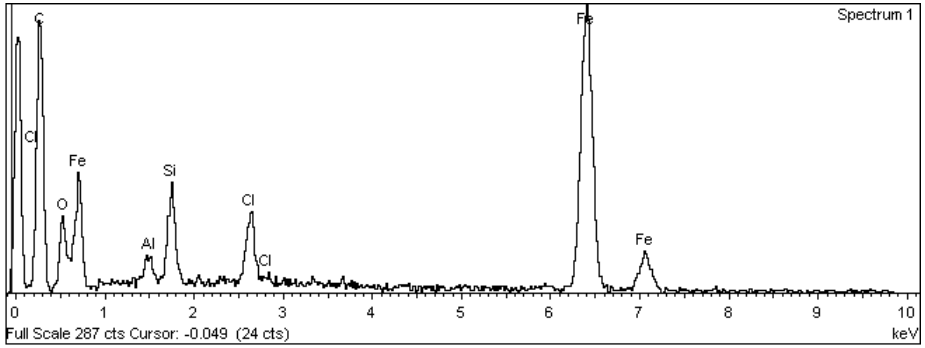

Spectrum 1
20µm
Electron Image 1

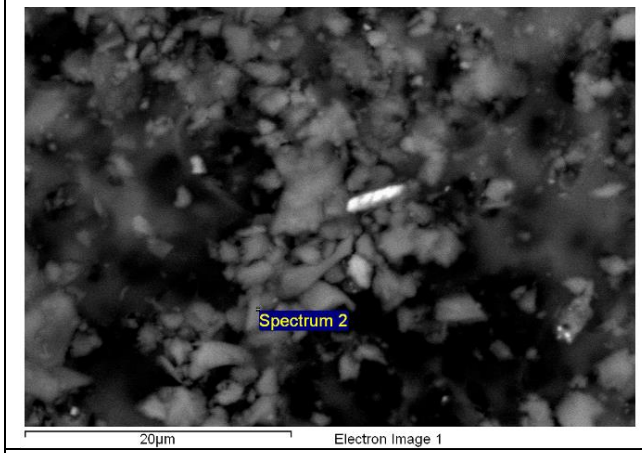

Spectrum 1
Si
O
K
Cl
Fe
Al
Cl
Cl
K
K
Fe
0
1
2
3
4
5
6
7
8
9
10
Full Scale 1961 cts Cursor: -0.049 (47 cts)
keV

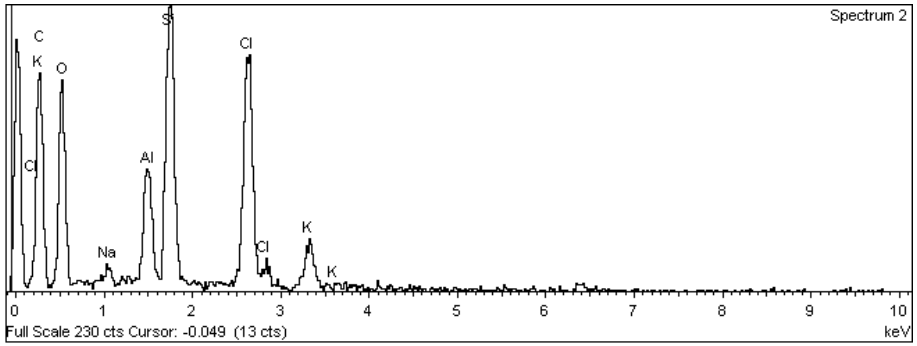

Spectrum 2
20µm
Electron Image 1

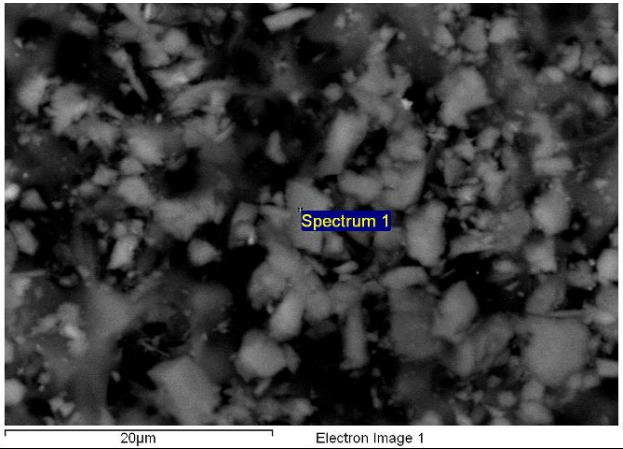

Spectrum 2
C
Ca
O
Mn
Cl
Fe
Al
Si
Cl
Ca
Ca
Mn
Fe
Mn
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 418 cts Cursor: -0.049 (57 cts)
keV

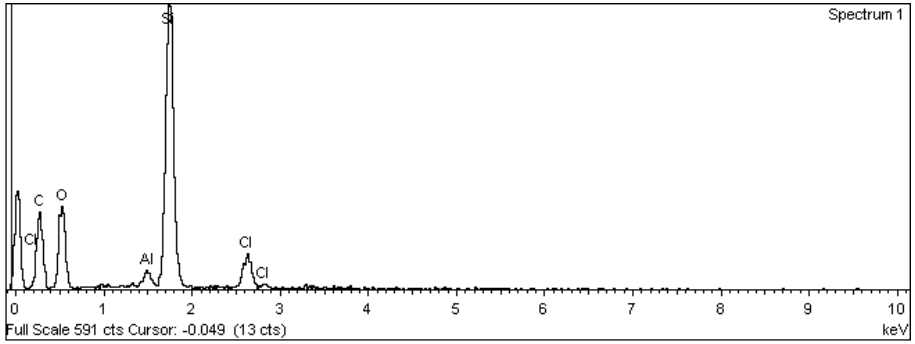

Spectrum 1
20µm
Electron Image 1

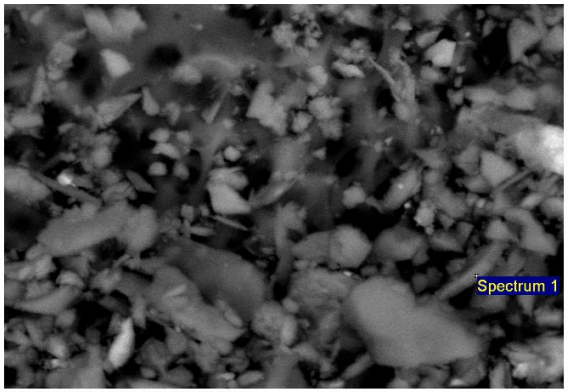

Spectrum 1
C
Cl
Fe
O
Al
Si
Cl
Cl
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 287 cts Cursor: -0.049 (24 cts)
keV

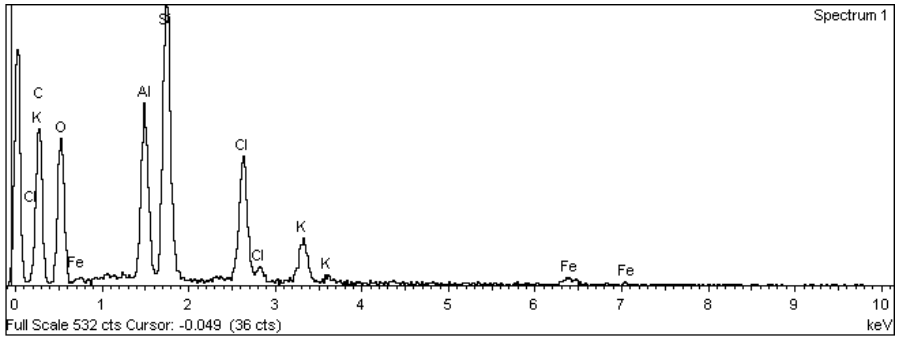

Spectrum 2
20µm
Electron Image 1

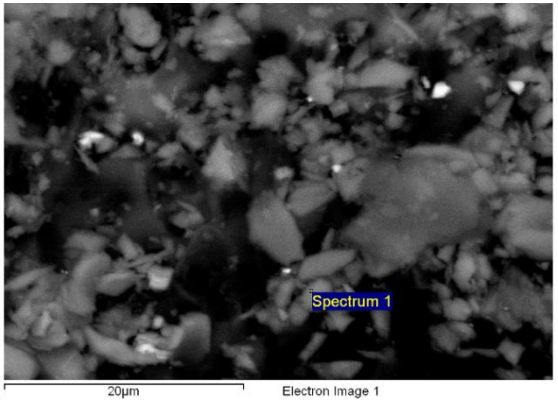

Spectrum 2
C
K
O
Cl
Na
Al
Si
Cl
K
Cl
K
0 1 2 3 4 5 6 7 8 9 10
Full Scale 230 cts Cursor: -0.049 (13 cts)
keV

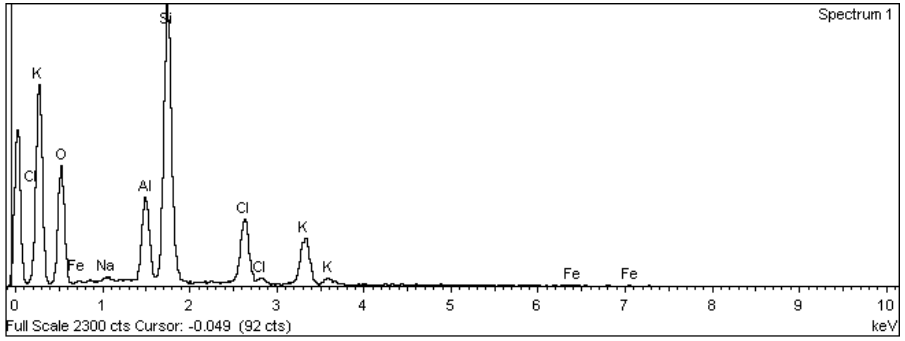

Spectrum 1
20µm
Electron Image 1

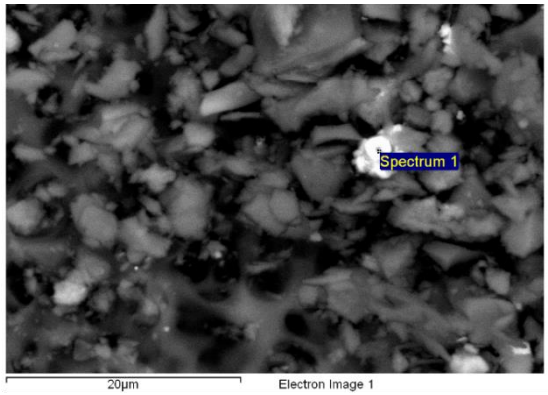

Spectrum 1
Si
C
O
Cl
Al
Cl
Cl
0 1 2 3 4 5 6 7 8 9 10
Full Scale 591 cts Cursor: -0.049 (13 cts)
keV

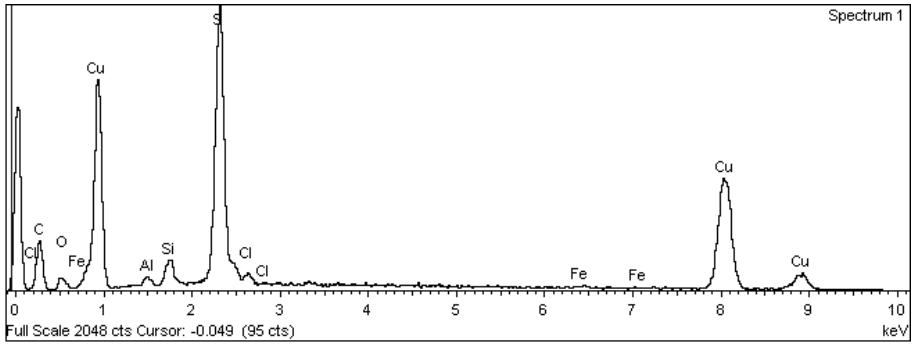

Spectrum 1
20µm
Electron Image 1

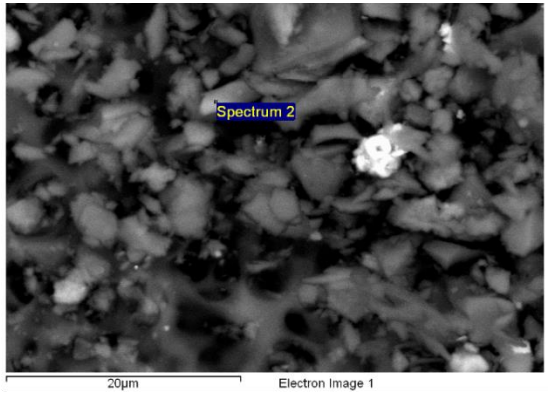

Spectrum 1
C
K
O
Al
Si
Cl
Fe
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 532 cts Cursor: -0.049 (36 cts)
keV

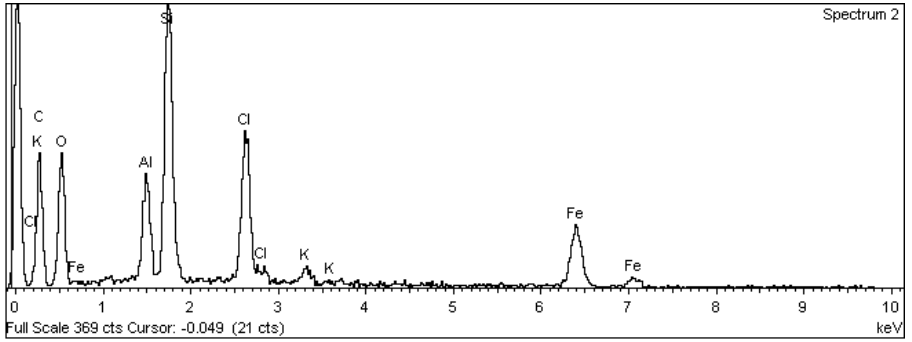

Spectrum 1
20µm
Electron Image 1

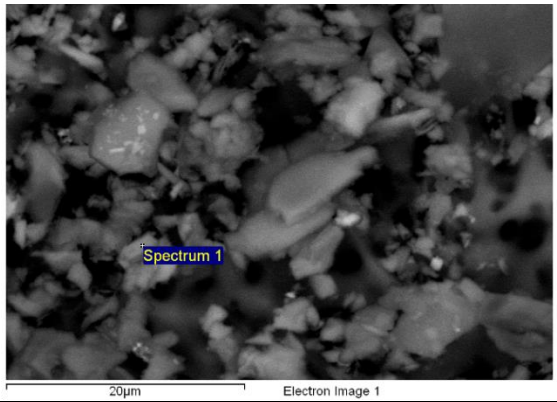

Spectrum 1
K
Cl
O
Al
Si
Fe
Na
Cl
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 2300 cts Cursor: -0.049 (92 cts)
keV


Spectrum 1
20µm
Electron Image 1

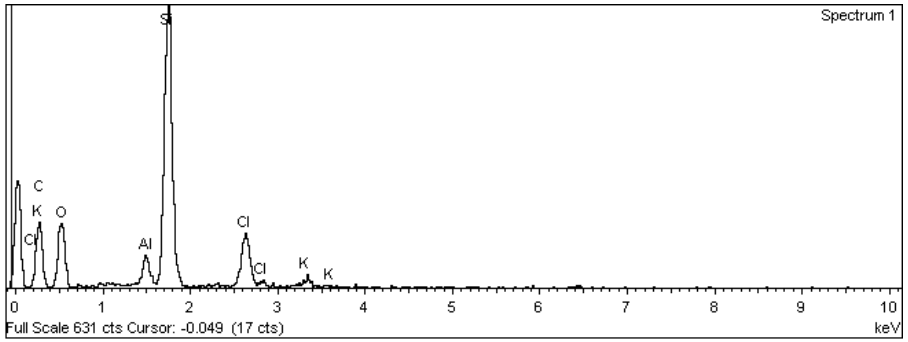

Spectrum 1
Cu
Si
C
Cl
O
Fe
Al
Si
Cl
Cl
Fe
Fe
Cu
Cu
0 1 2 3 4 5 6 7 8 9 10
Full Scale 2048 cts Cursor: -0.049 (95 cts)
keV


Spectrum 2
20µm
Electron Image 1


Spectrum 2
Si
C
K
O
Cl
Al
Cl
Fe
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 369 cts Cursor: -0.049 (21 cts)
keV



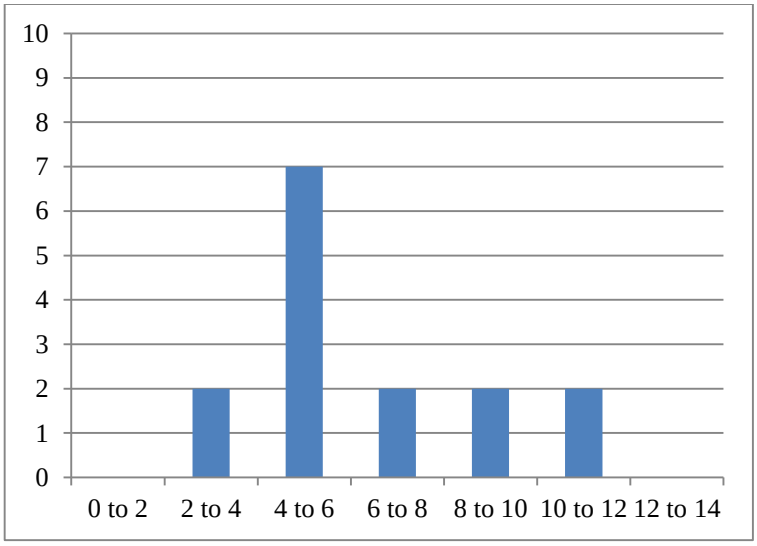
I7 EM micrograph images for F5007



I8 Elemental spectrums for F5007

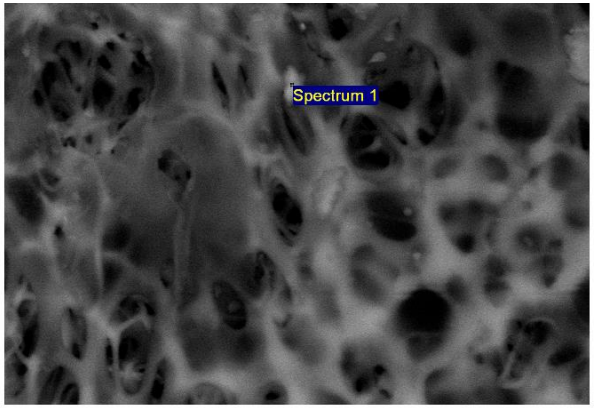
I9 Elemental scan for F5723

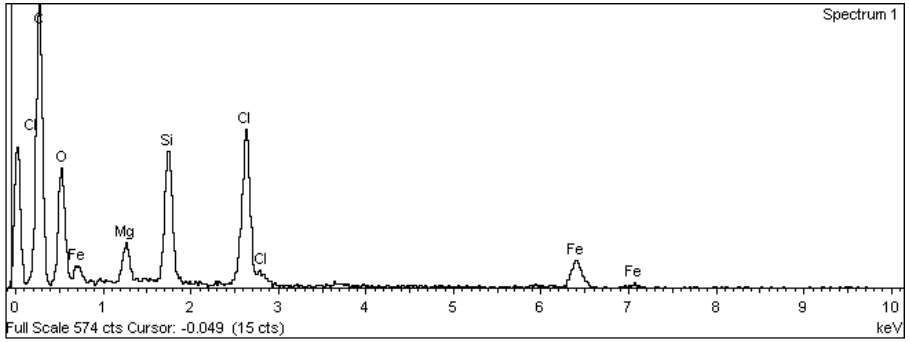
Fibre #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	2/1	5.7	O, Si	Al, Na
2	3/1	2.4	O, Si	Al, Fe, Mg
3	4/1	11.0	O, Si	Al, Fe, Mg
4	5/1	4.5	O, Si	Al, Ca
5	6/1	5.5	O, Si	Al, Ca
6	7/1	4.8	O, Si	Al, Ca, Fe
7	8/1	3.8	O, Si	Al, Na
8	9/1	10.6	-	Si
9	10/1	8.5	O, Si	Al, Fe, Ca, Mg, Na
10	11/1	6.4	O, Si	Al, Fe, Mg, Ca, K
11	11/2	4.8	O, Si	Al, Fe, Mg, Ca
12	12/1	8.9	O, Si	Al, K, Ba
13	13/1	5.8	O, Si	Al, K, Fe, Mg
14	14/1	4.4	O, Ca	Si, Al
15	15/1	6.6	O, Si	Al, Fe, Mg



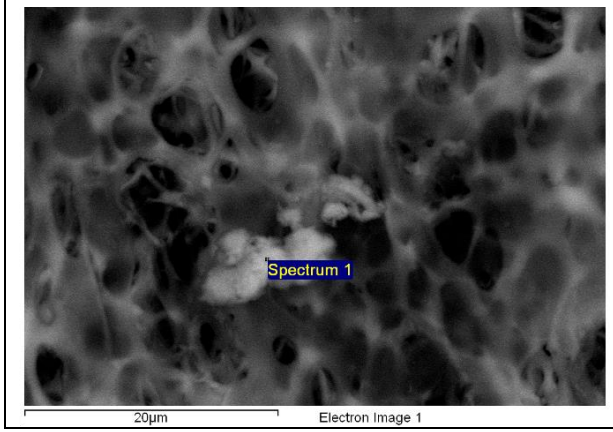
I10: Particle size distribution for F5723

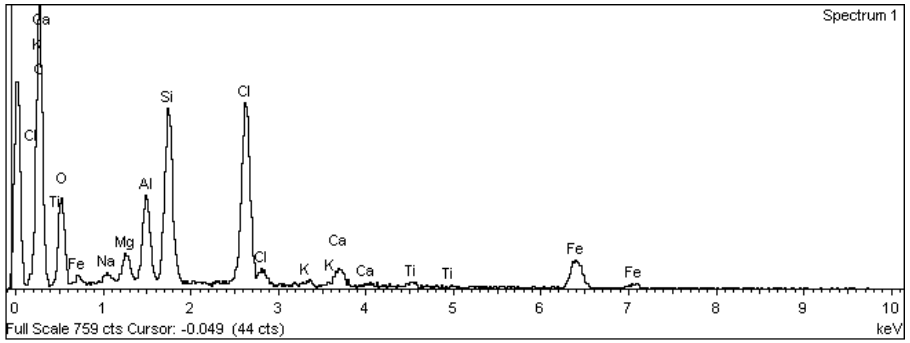
F5723



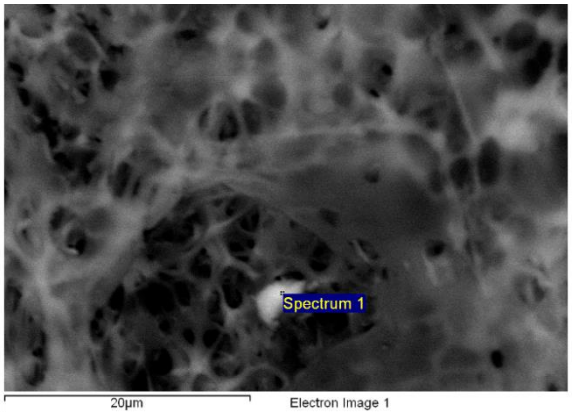


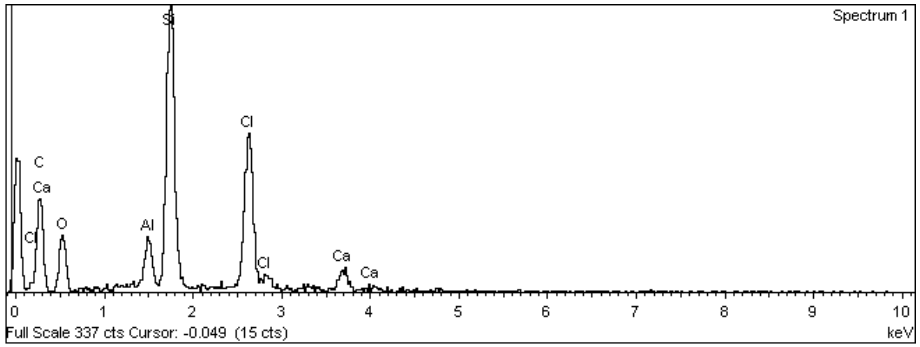
Site of interest 3



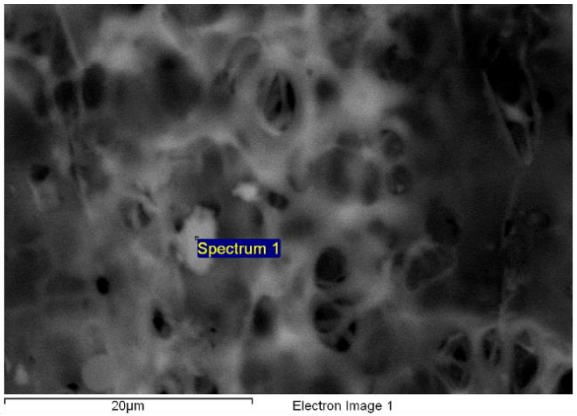


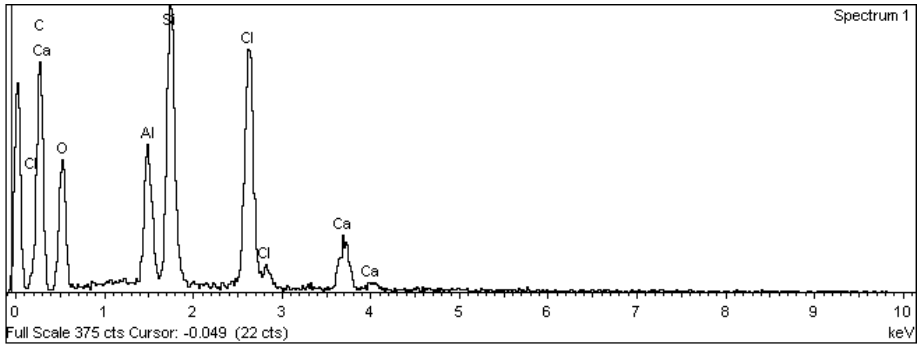
Site of interest 4



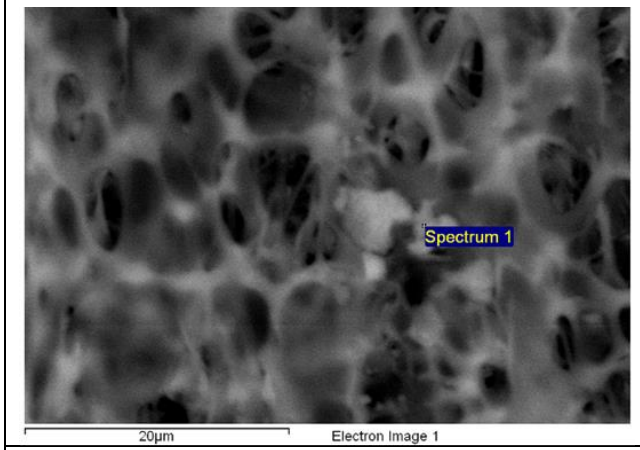


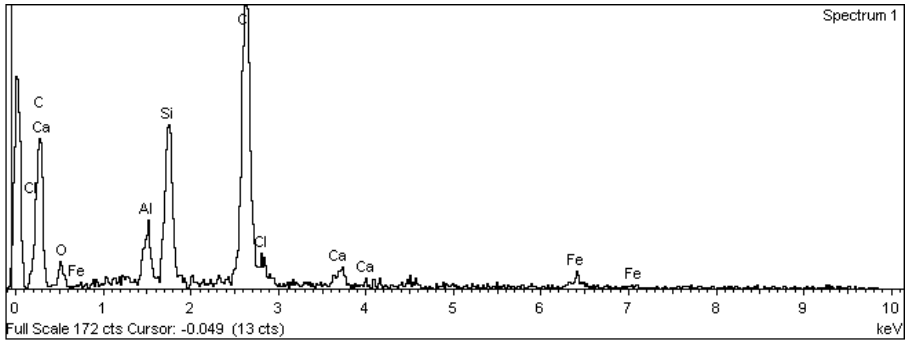
Site of interest 5



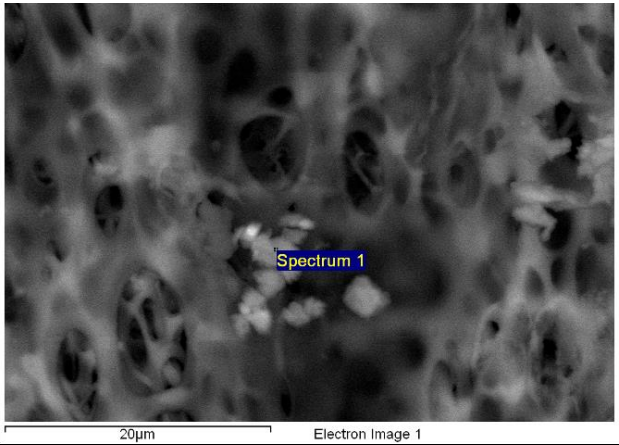


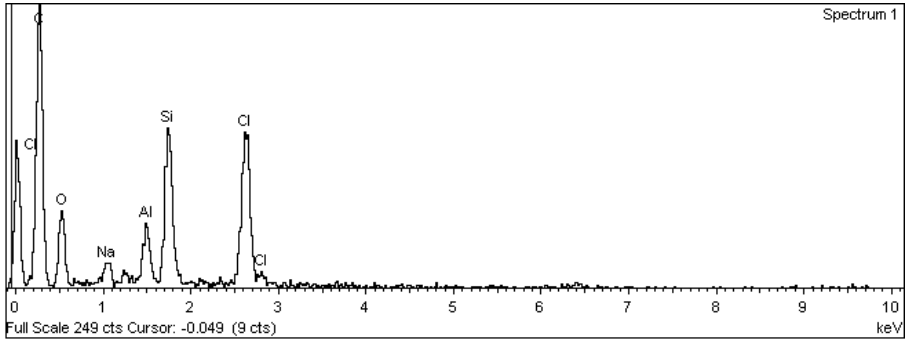
Site of intest 6



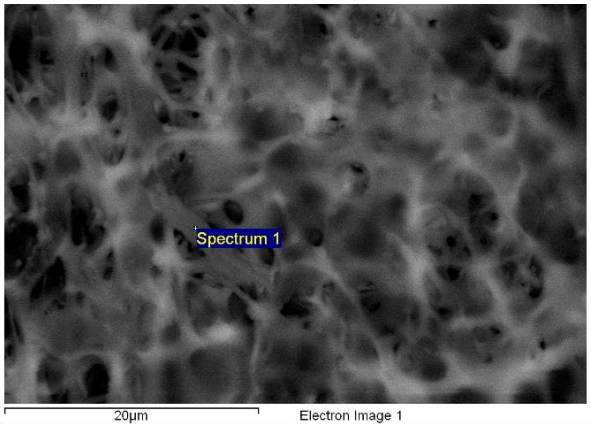


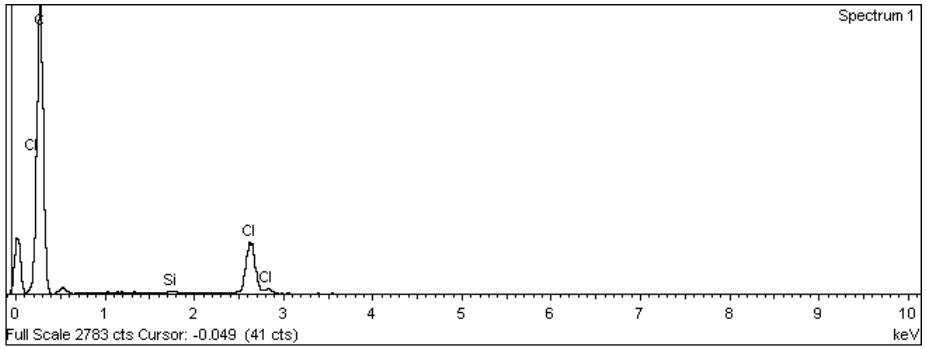
Site of interest 7



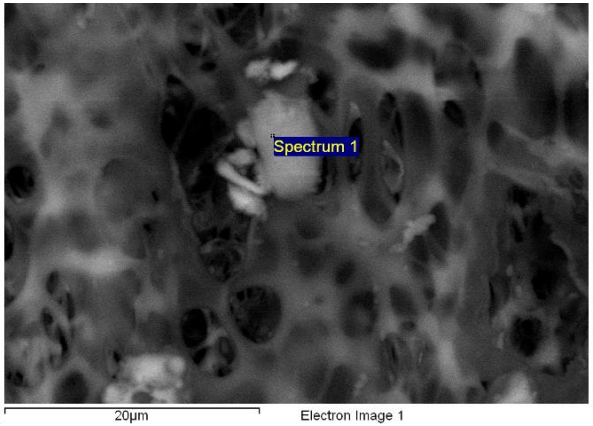


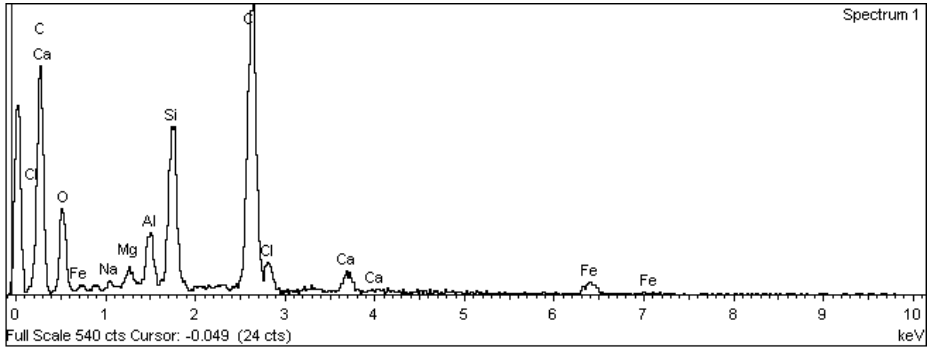
Site of interest 8



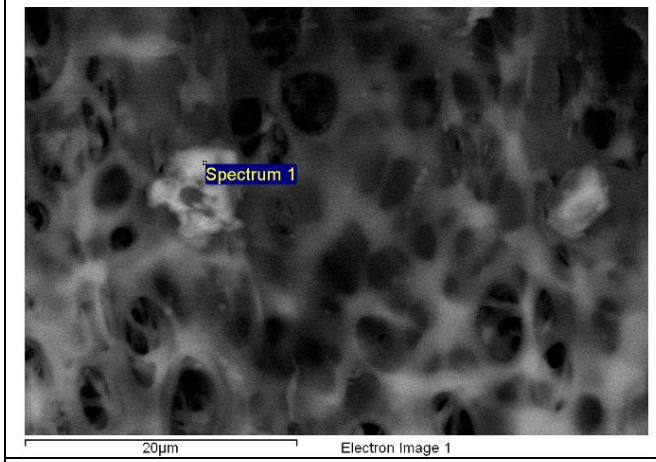


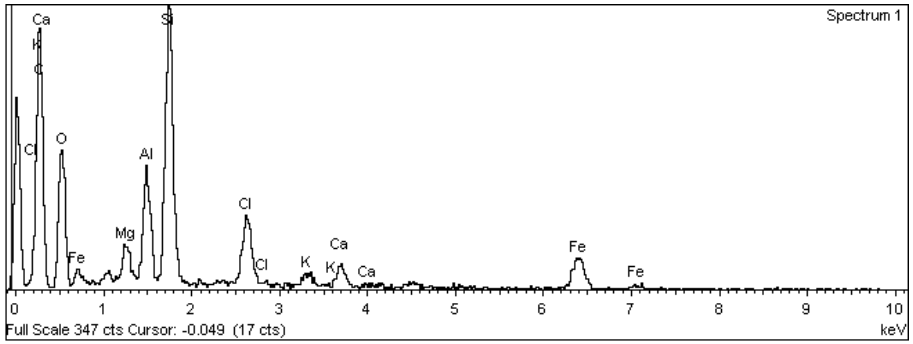
Site of interest 9



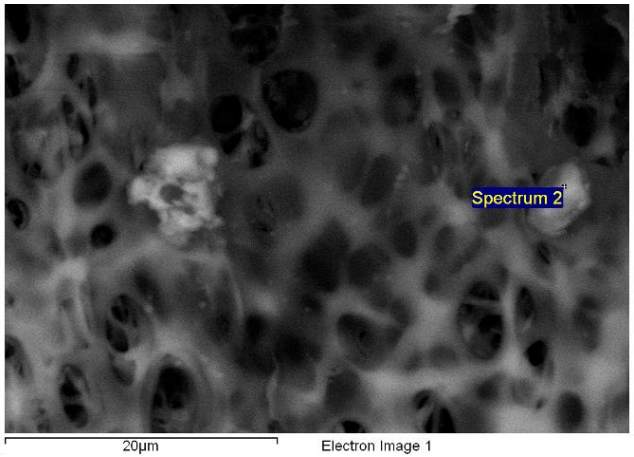


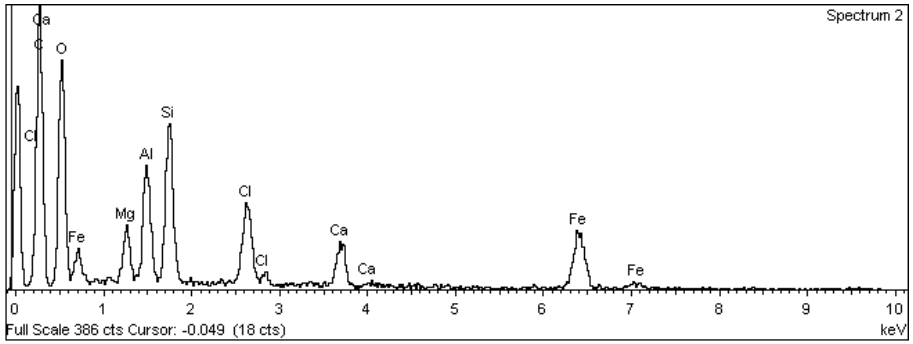
Site of interest 10



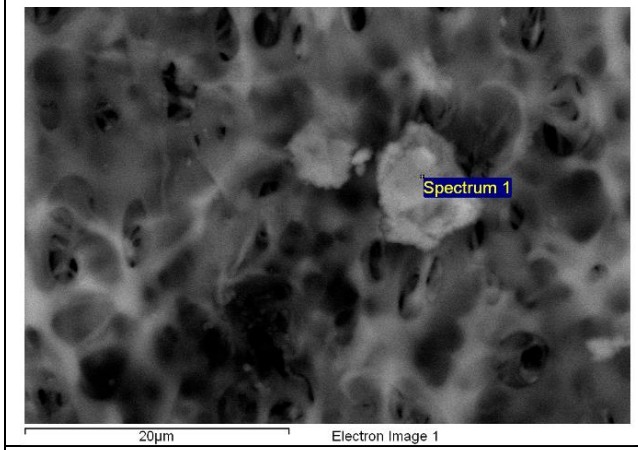


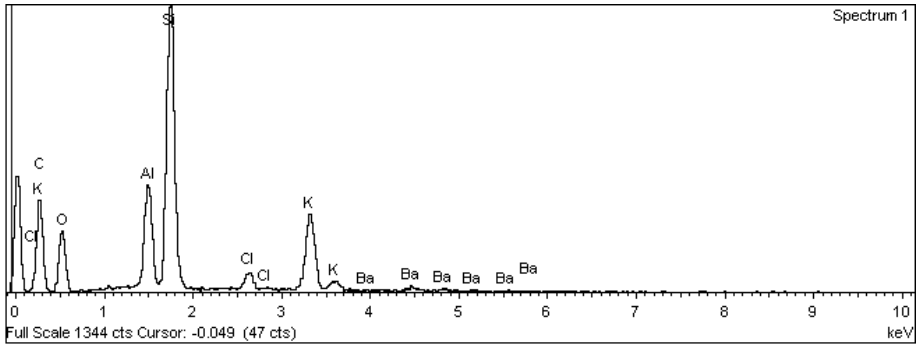
Site of interest 11



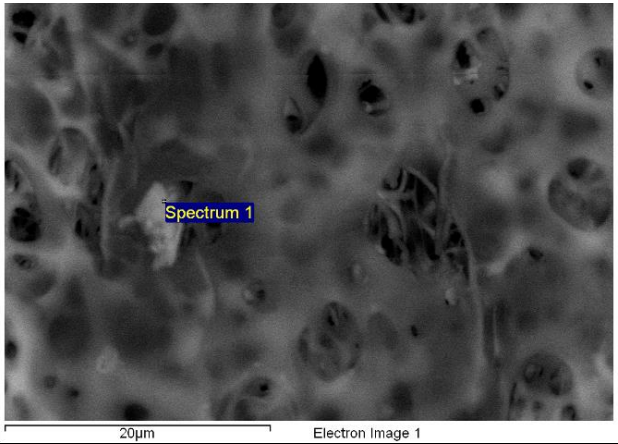


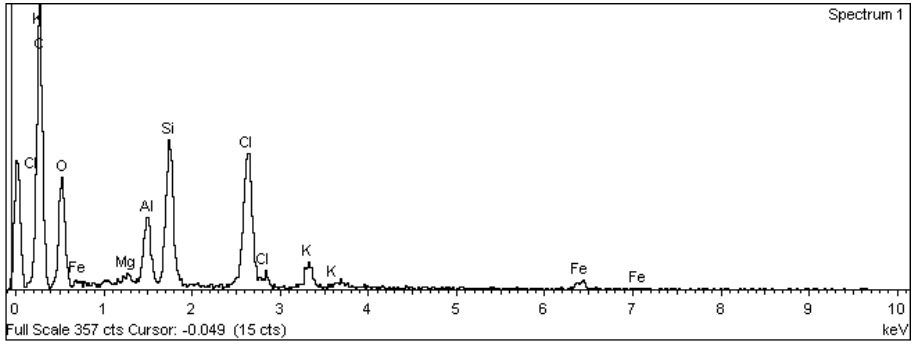
Site of interest 11



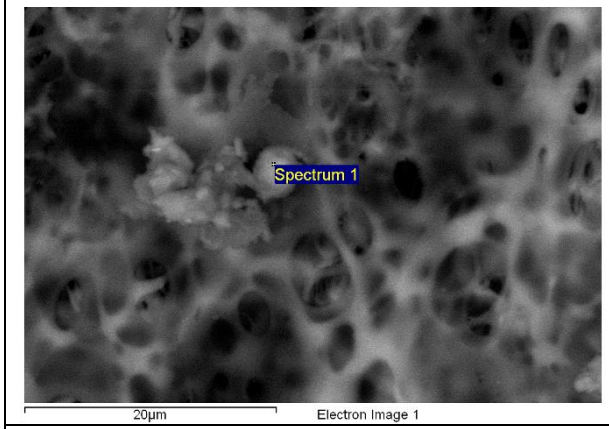


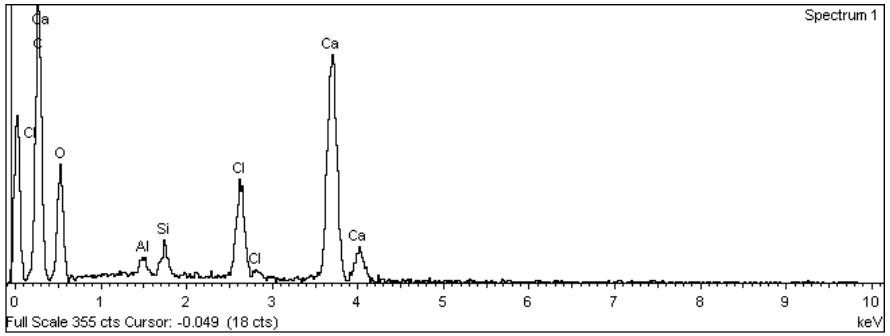
Site of interest 12



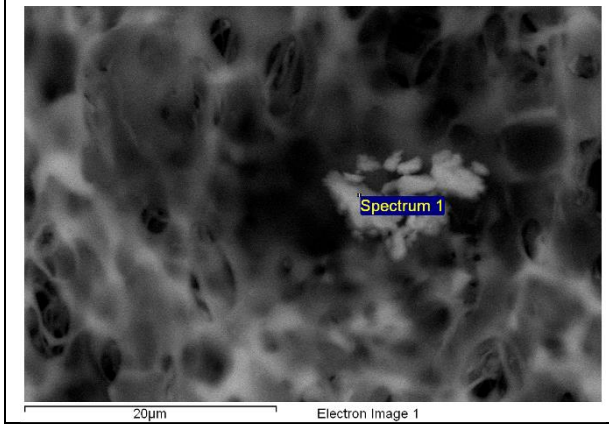


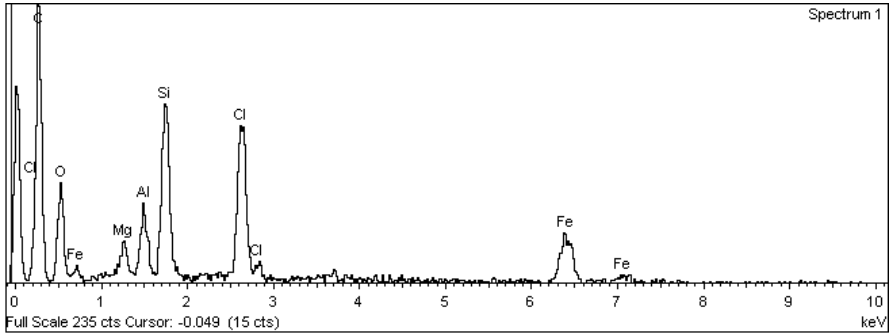
Site of interest 13



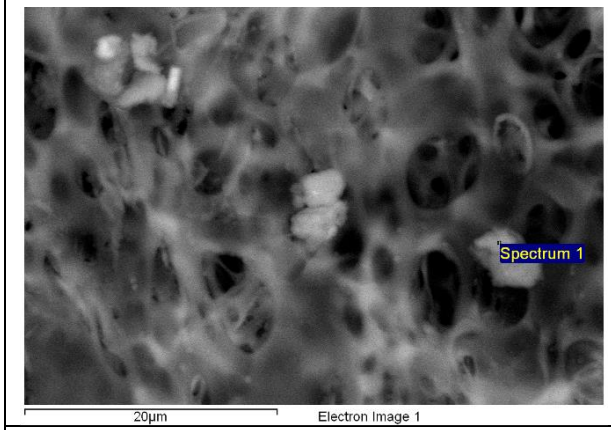


Site of interest 14

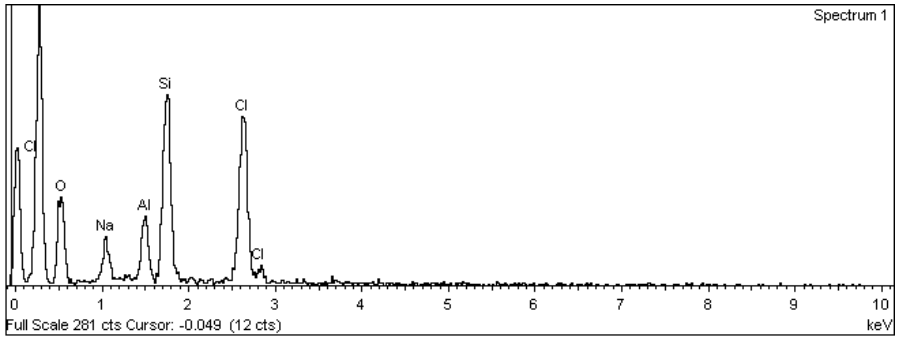




Site of interest 15



I11 EM micrograph images for F5723

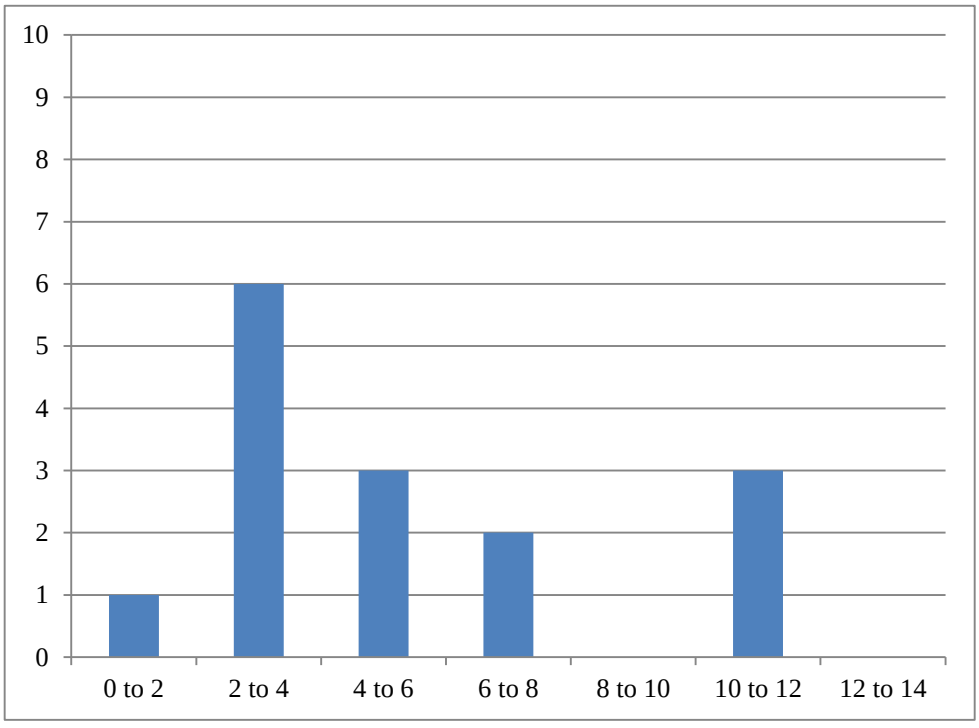


Site of interest 2

I12 Elemental spectrums for F5723

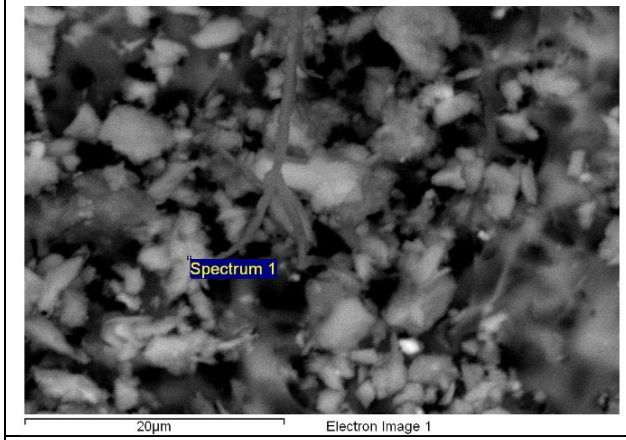
I13 Elemental scan for F6439

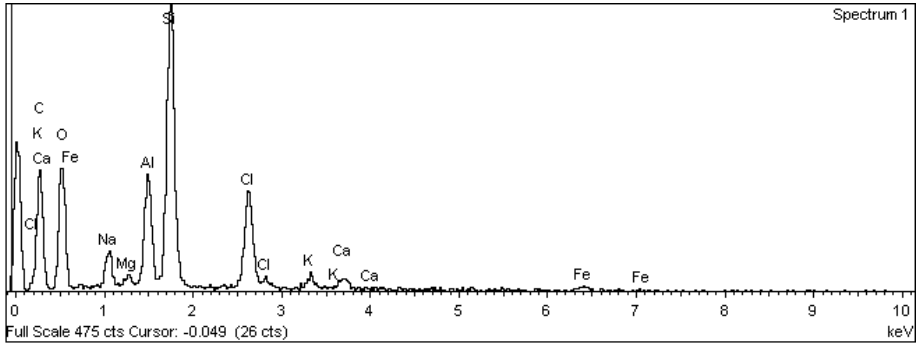
Fibre #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	1/1	6.4	O, Si	Al, Na, Mg, Ca, K, Fe
2	1/2	1.8	O, Fe	Si, Al, Na, Ca
3	1/3	10.5	O, Si	Al, Ca, K, Mg, Fe
4	3/1	7.3	O, Si	Al, K, Mg, Fe
5	4/1	3.0	O, Si	Al, Mg, Fe, Ca
6	5/1	4.1	O, Si	Al, Na, Ca, K
7	6/1	2.6	O, Si	Mg, Al, Fe, Ca
8	7/1	4.8	O, Fe, Ti	Si, Al
9	8/1	2.4	O, Si	Al, Na, Mg, Ca
10	10/2	3.5	O, Si	Al, Ca, Fe
11	11/1	2.1	O, Si	Al, K, Ca
12	12/1	10.2	O, Si	Al, K, Mg
13	13/1	3.2	O, Si	Al
14	14/1	10.9	O, Si	Al, K, Mg, Fe
15	15/1	4.9	O, Si	Na, Al



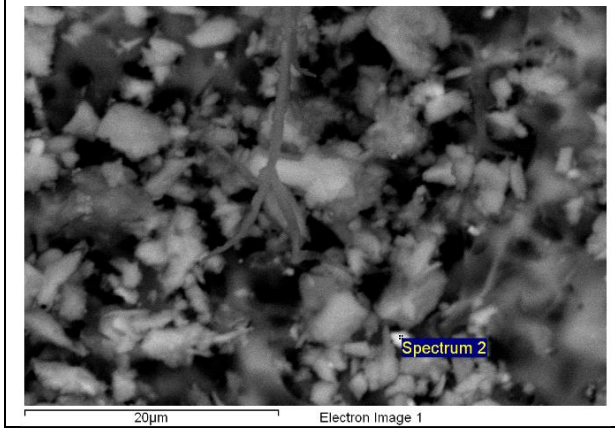
I14: Particle size distribution for F6439

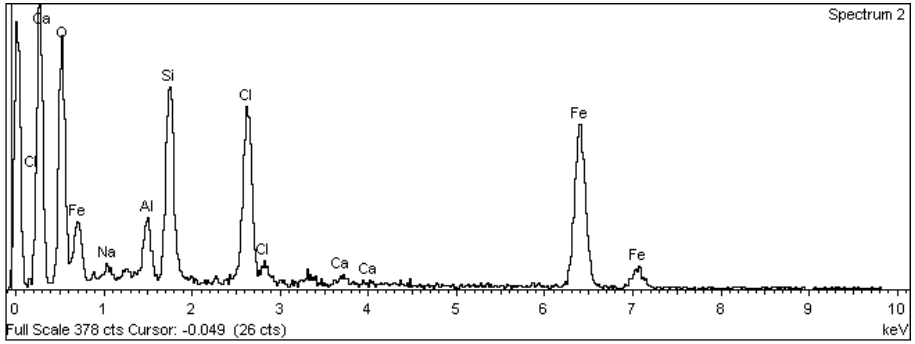
F6439



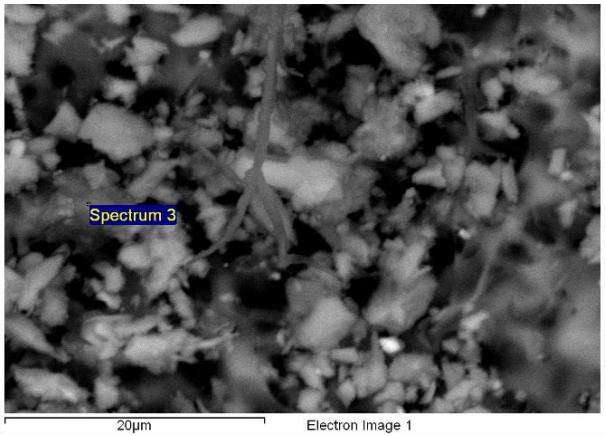


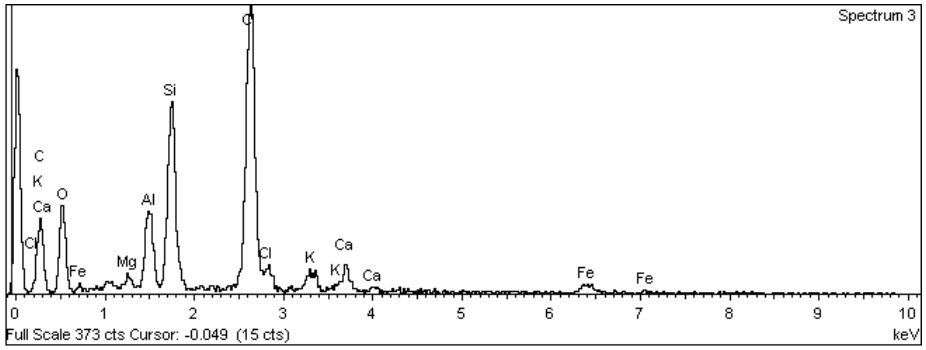
Particle 1



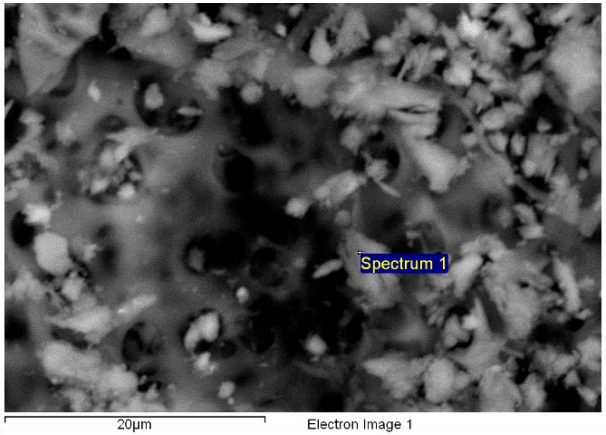


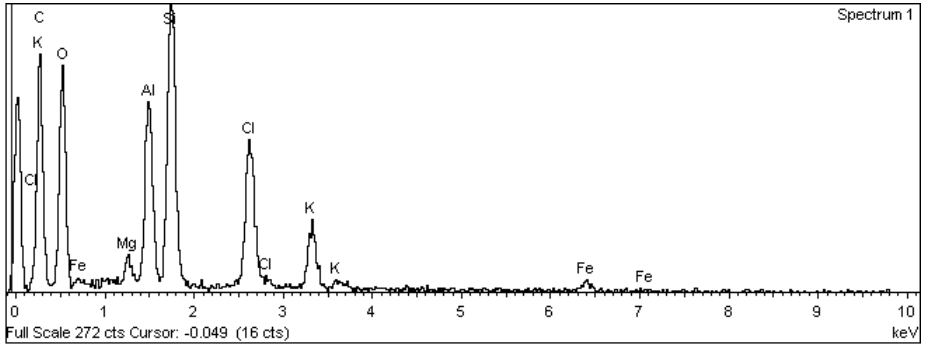
Particle 2



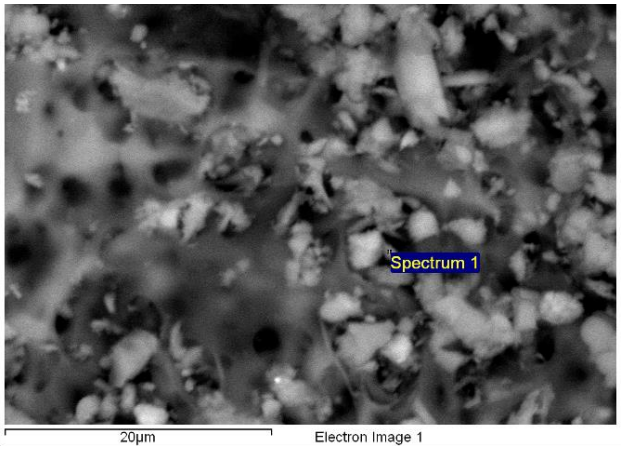


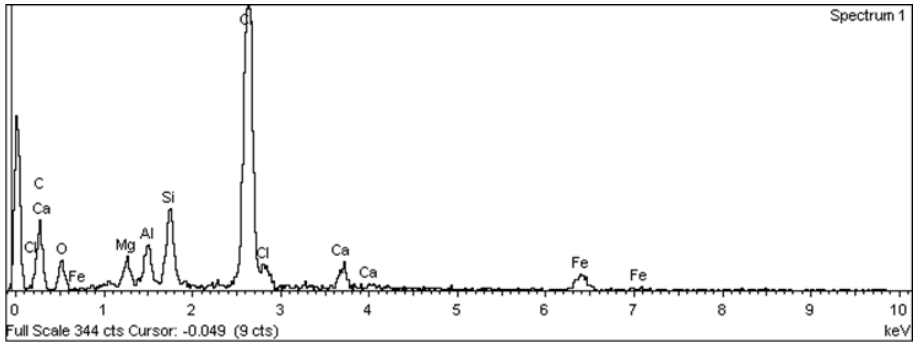
Particle 3



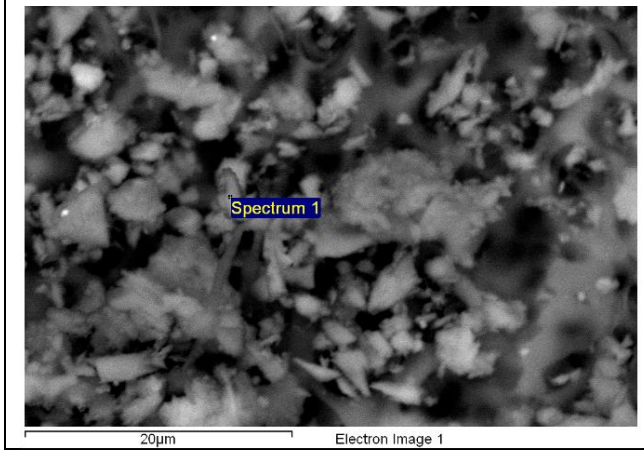


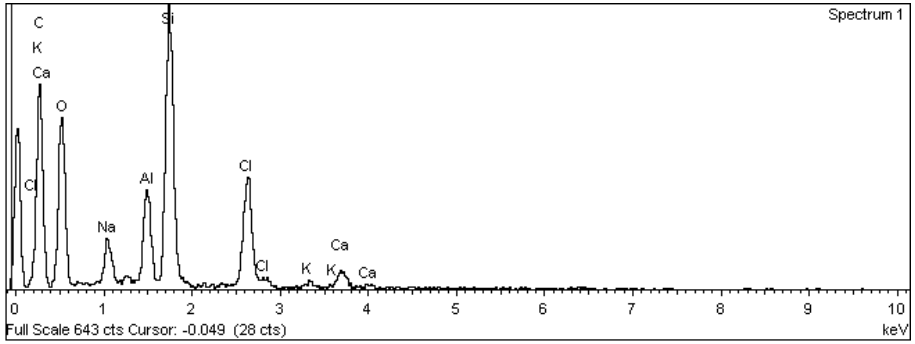
Particle 4



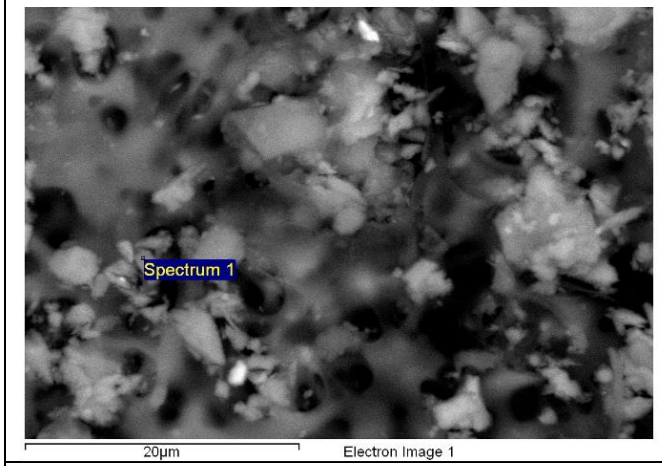


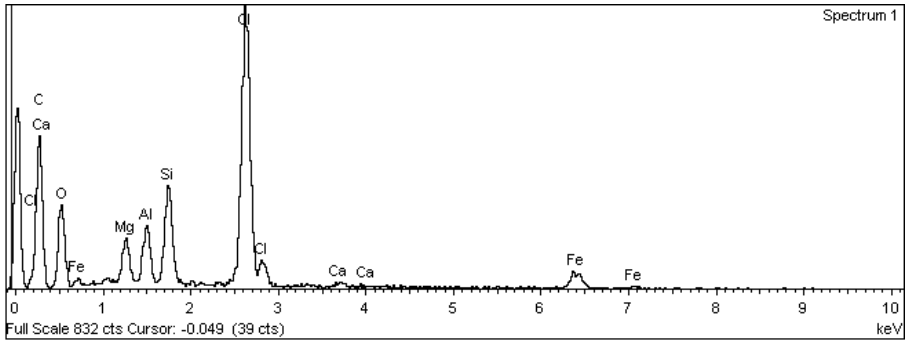
Particle 5



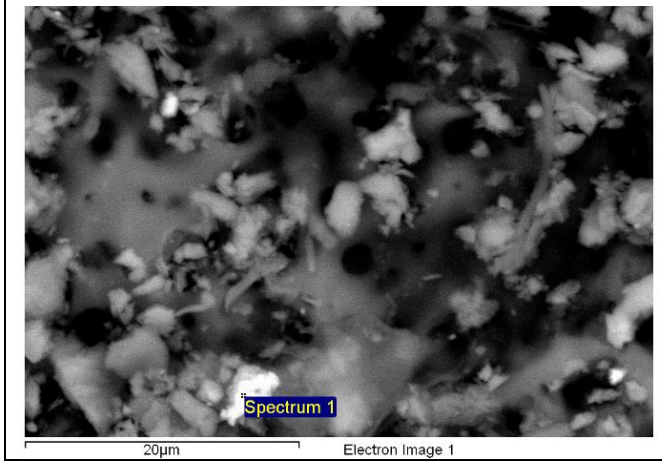


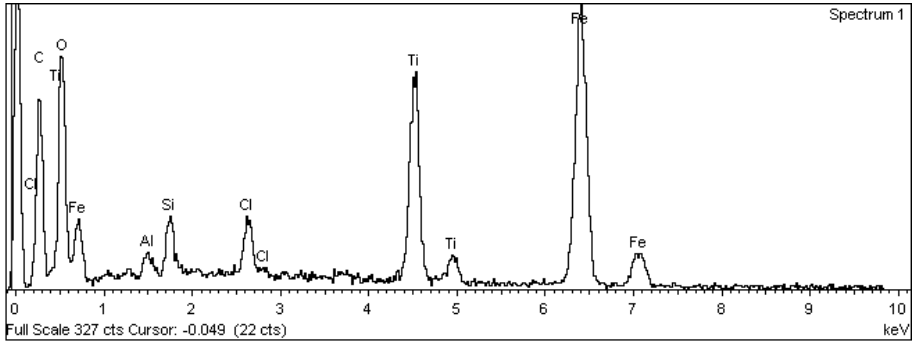
Particle 6



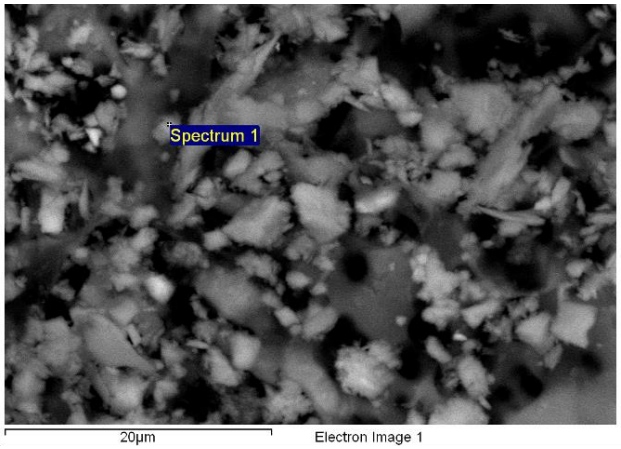


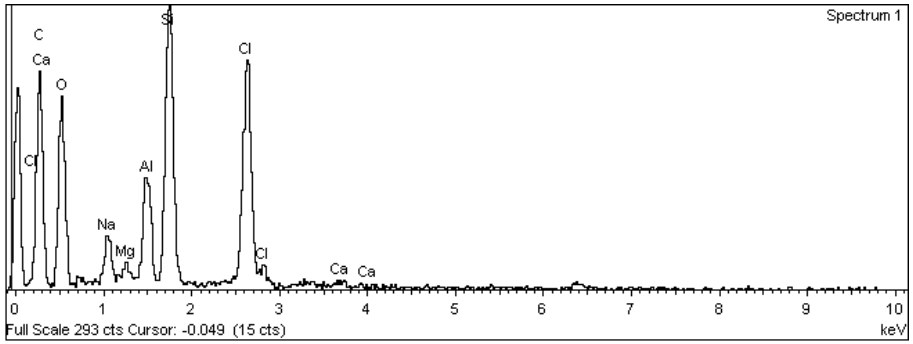
Particle 7



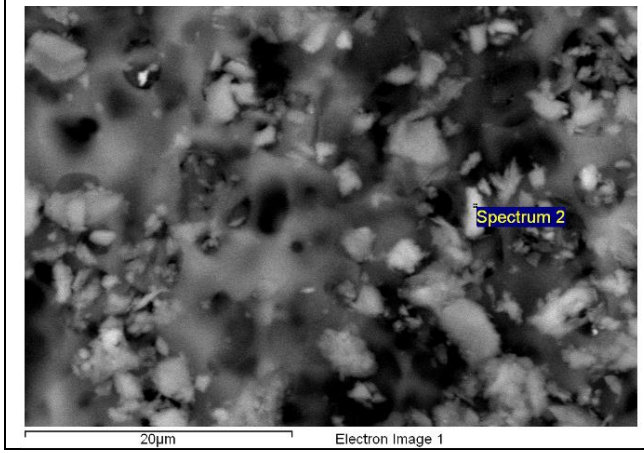


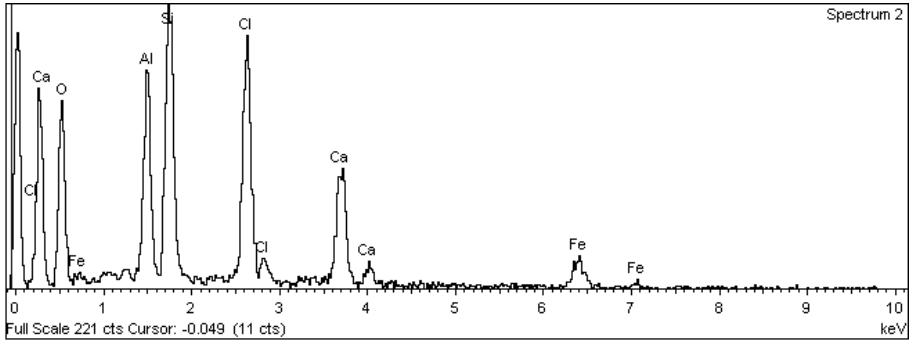
Particle 8



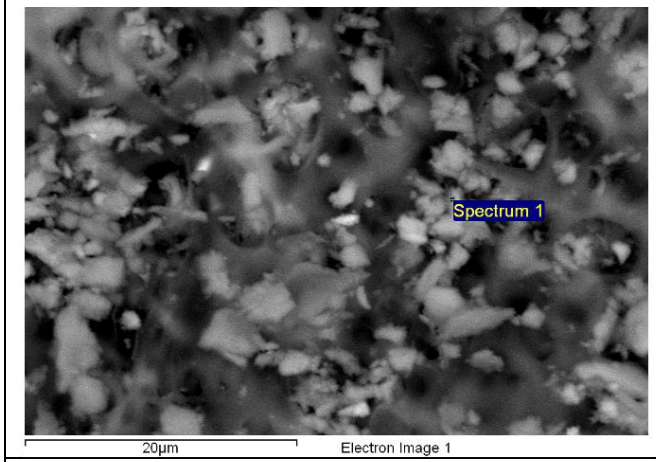


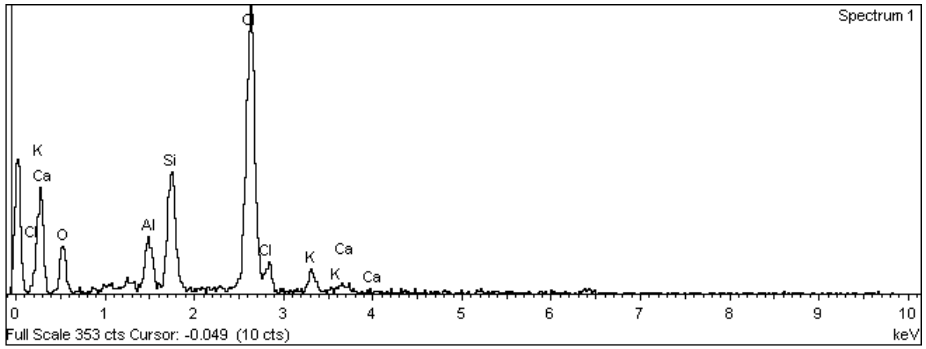
Particle 9



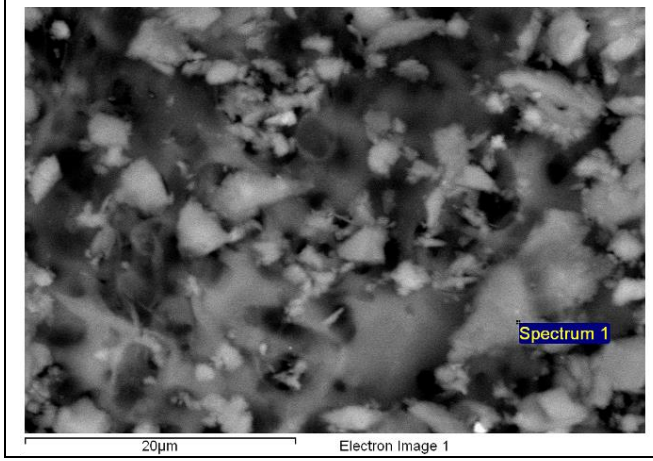


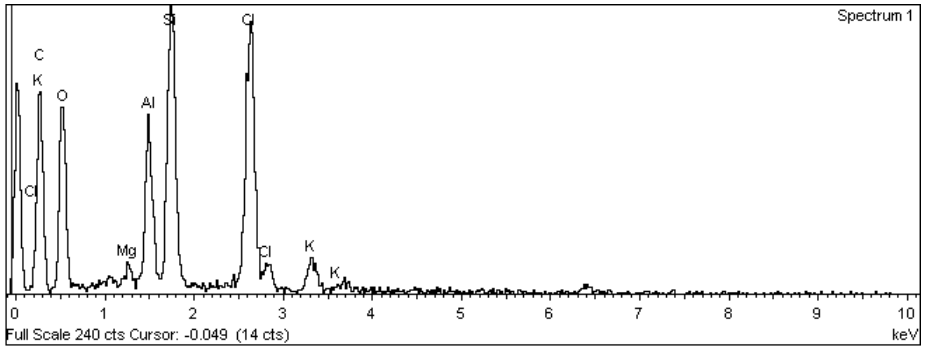
Particle 10



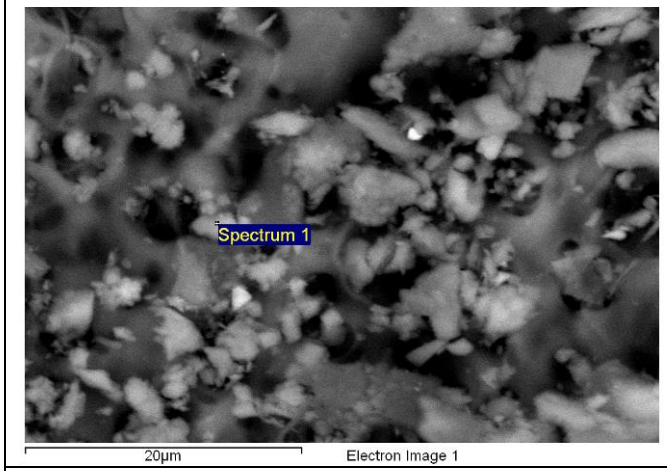


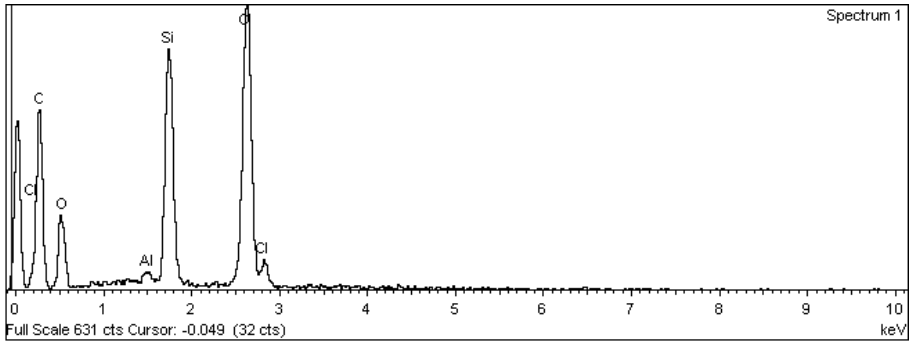
Particle 11



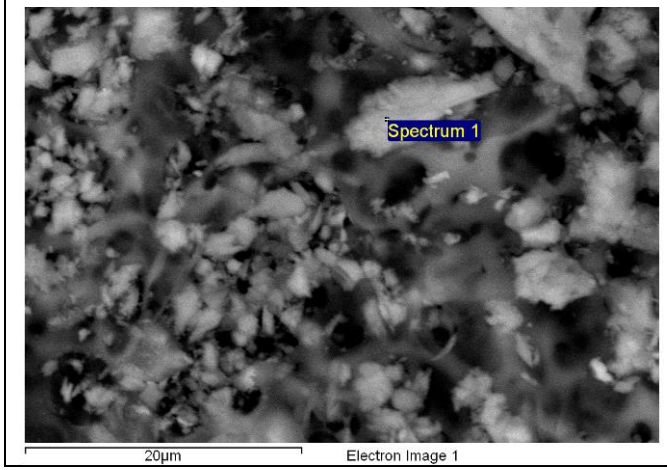


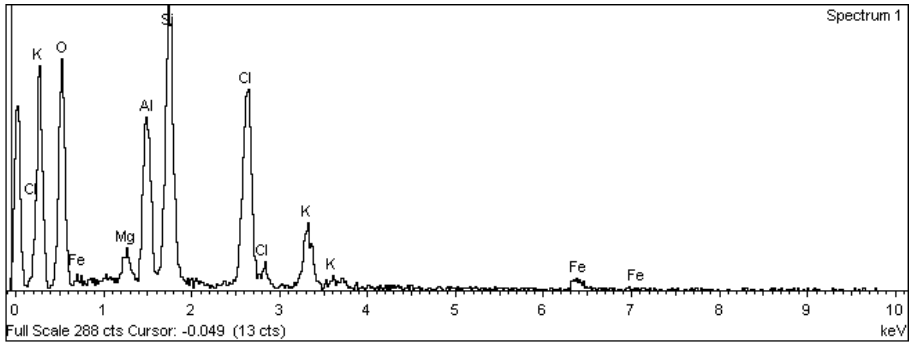
Particle 12



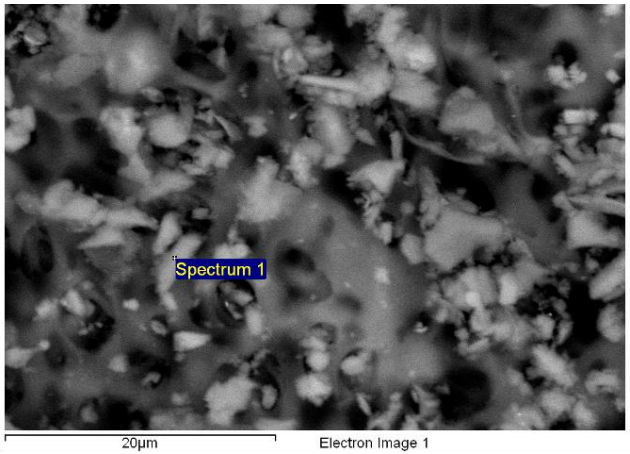


Particle 13

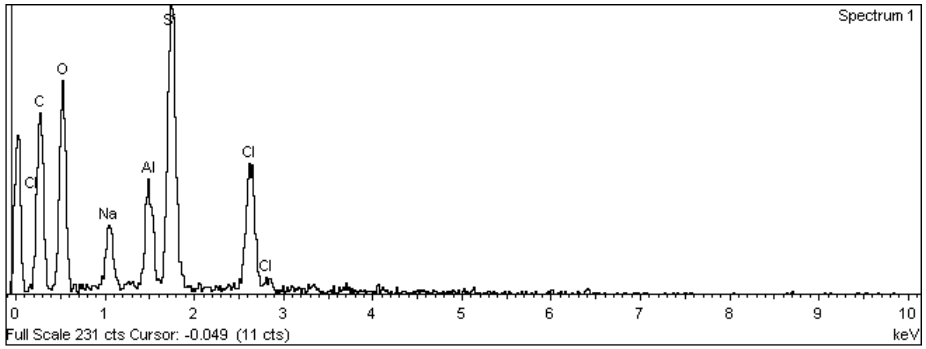




Particle 14



I15 EM micrograph images for F6439

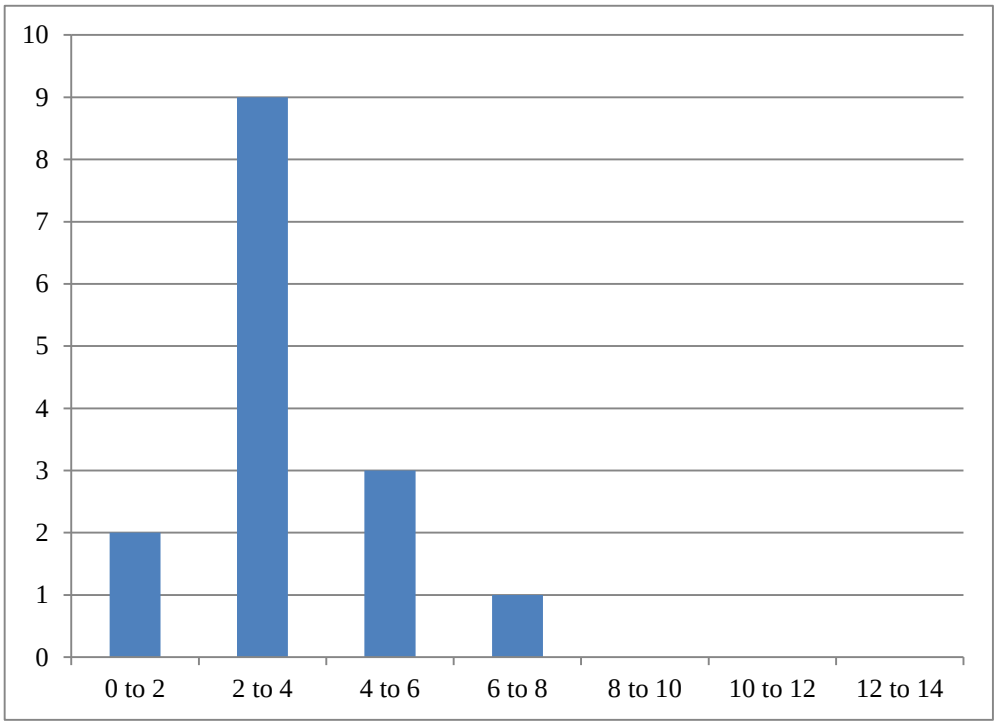


Particle 15

I16 Elemental spectrums for F6439

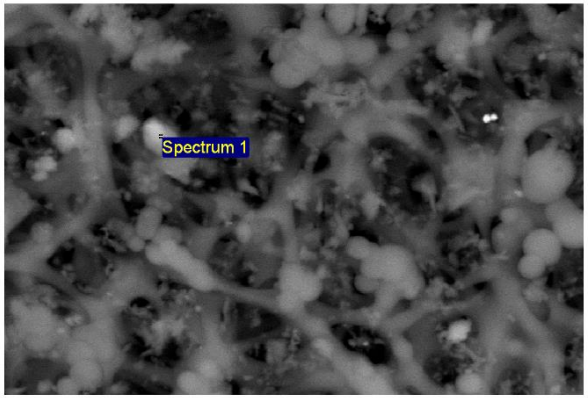
I17 Elemental scan for F6725

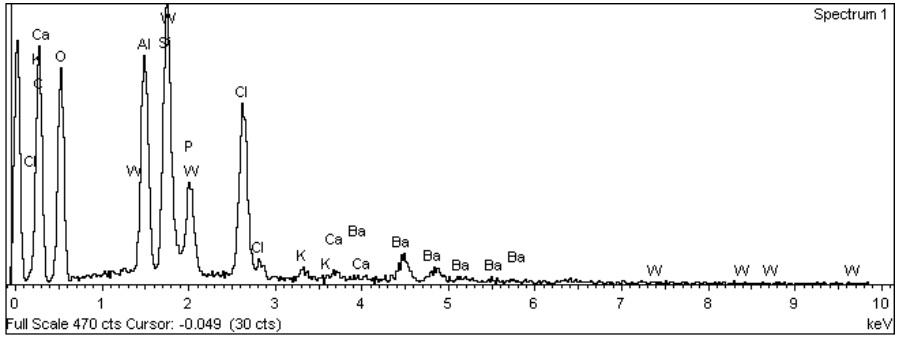
Particle #	Image/Field #	Diameter (μm)	Major Elements	Minor Elements
1	2/1	3.1	O, Si, Al	P, Ba, K, Ca
2	2/2	2.2	O, Ca	Si
3	2/3	0.6	O, Cu	Si, Al
4	3/2	2.5	O, Ti	Si, Al, Fe
5	4/1	6.0	O, Fe	Si, Al
6	5/1	2.4	O, Fe, Ti	Si, Al
7	6/2	3.3	O, Si, Al	-
8	7/2	3.3	O, Fe	Si, Al
9	8/2	5.9	O, Si, Al	-
10	9/1	4.1	O, Si, Al	Mg, Fe
11	10/1	6.4	O, Fe	Si, Al
12	11/2	2.3	O, Si	-
13	12/1	0.9	O, Cu	Si, Al
14	13/1	2.1	O, Fe, S	Si, Al, Ca
15	13/2	3.5	O, Si, Al	-



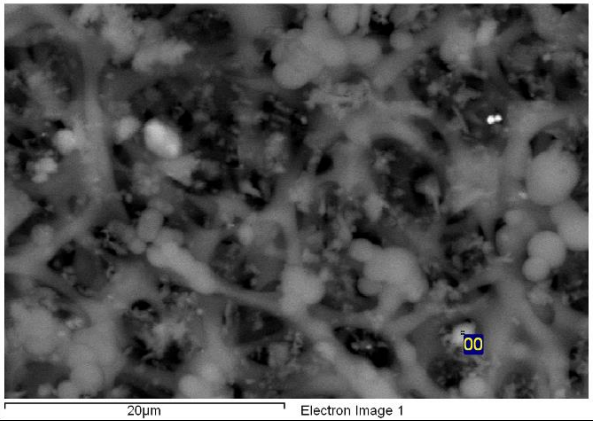
I18: Particle size distribution for F6725

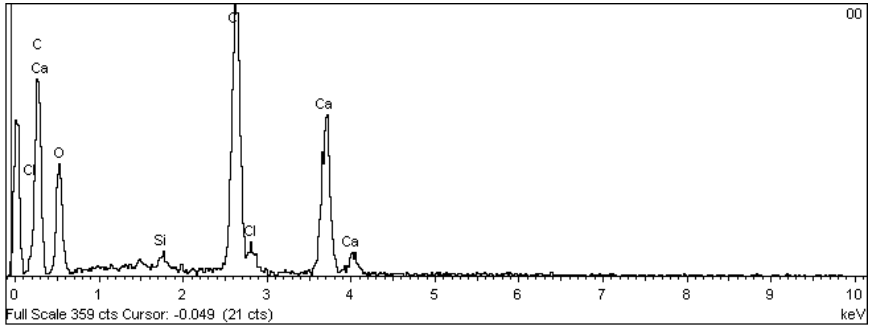
F6725



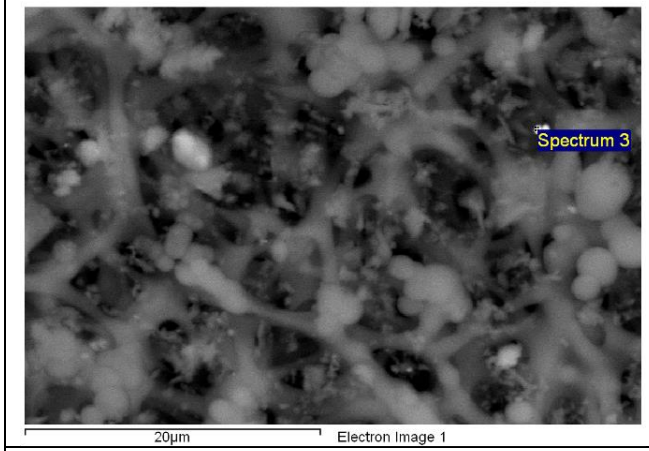


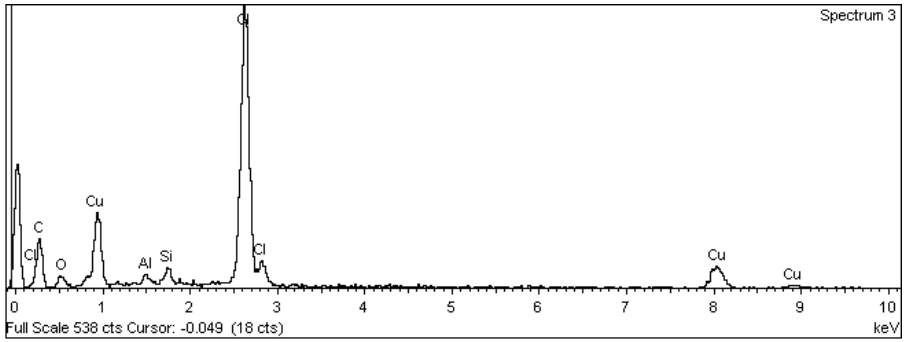
Site of interest 2



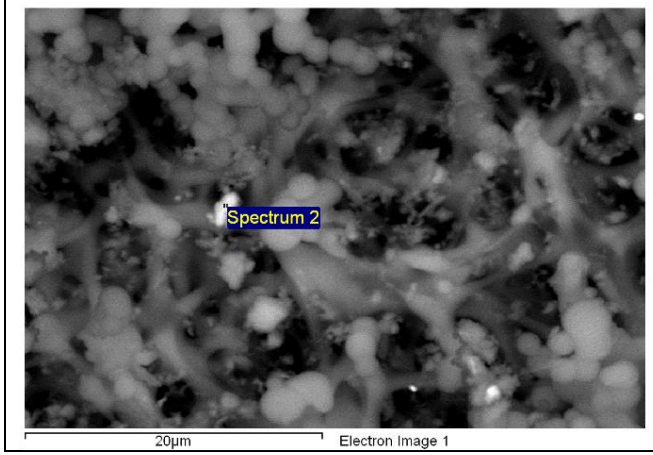


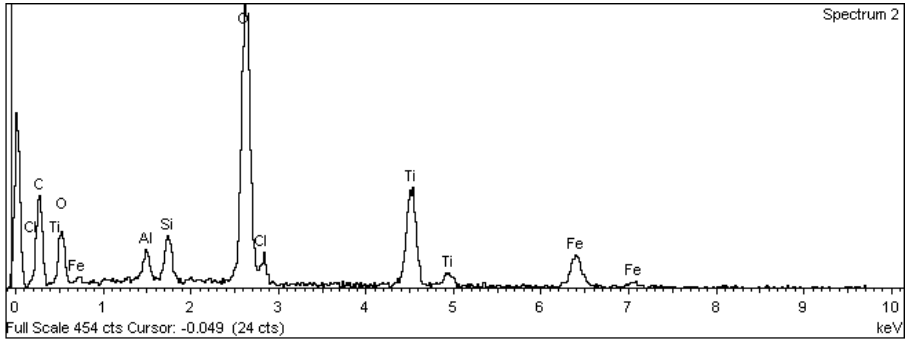
Site of interest 2



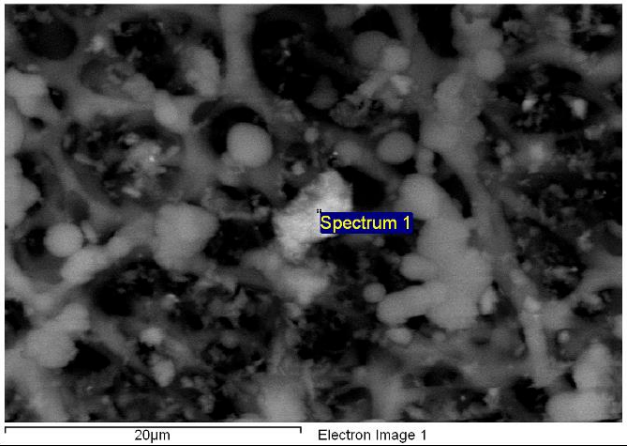


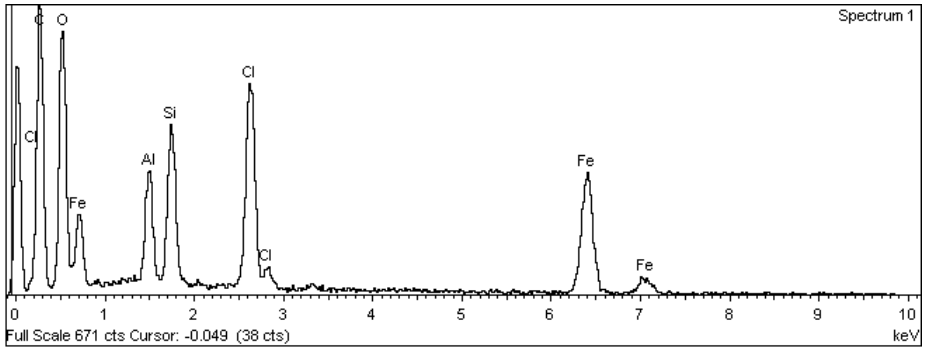
Site of interest 2



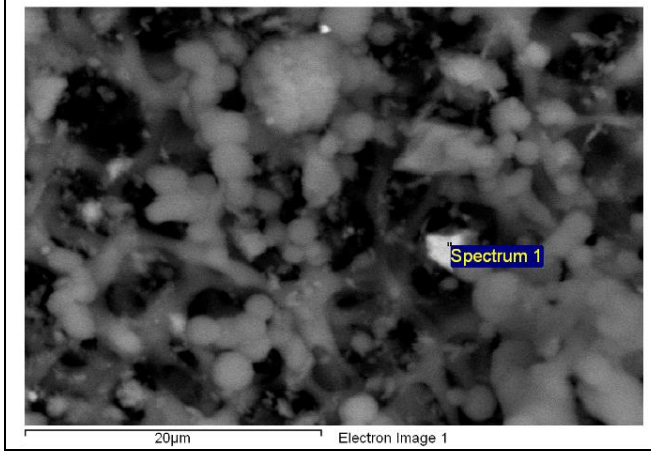


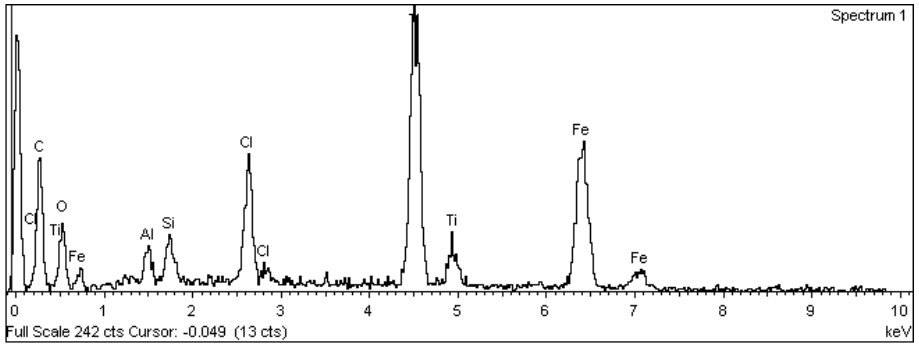
Site of interest 3



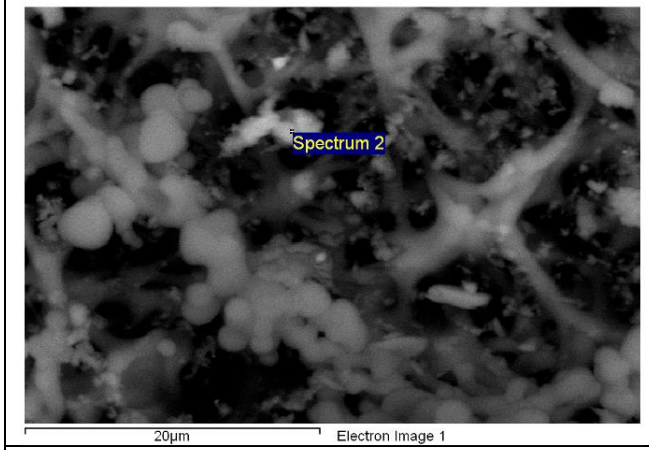


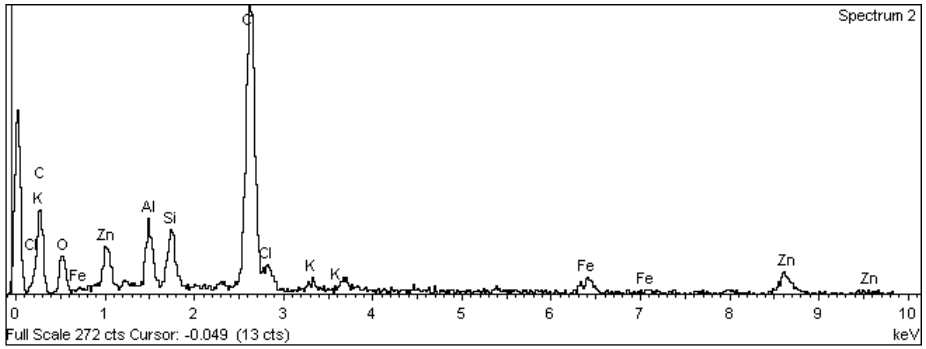
Site of interest 4



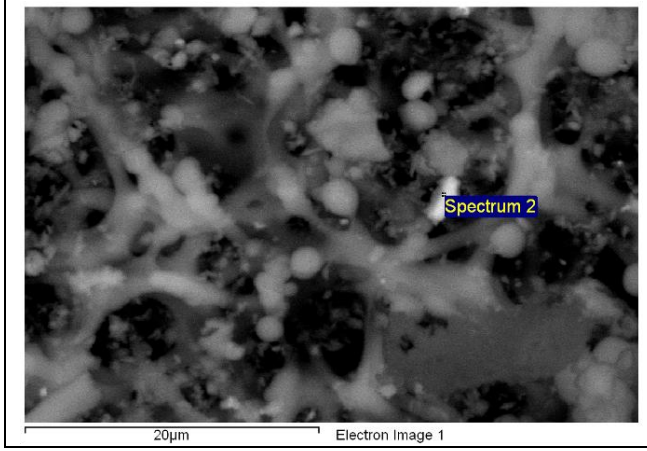


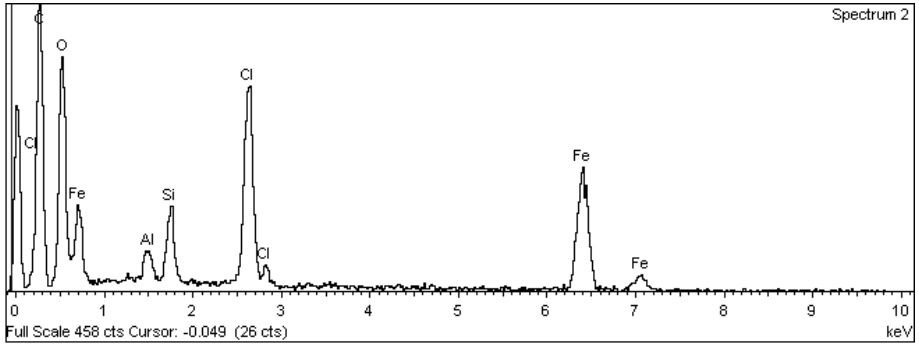
Site of interest 5



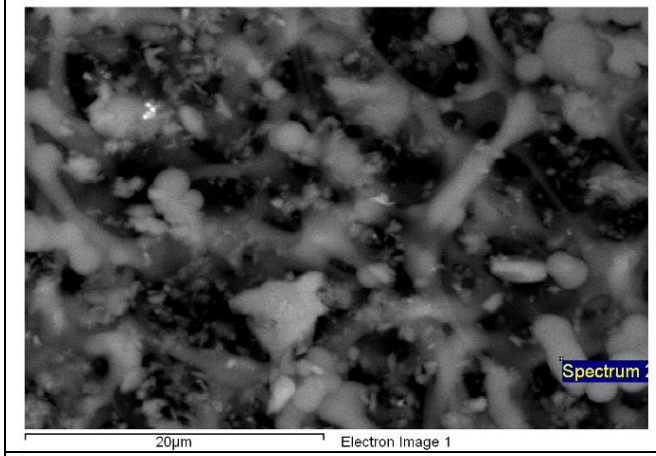


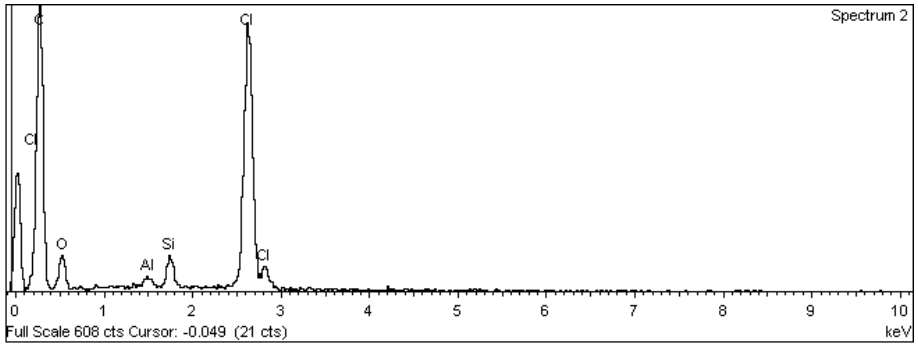
Site of interest 6



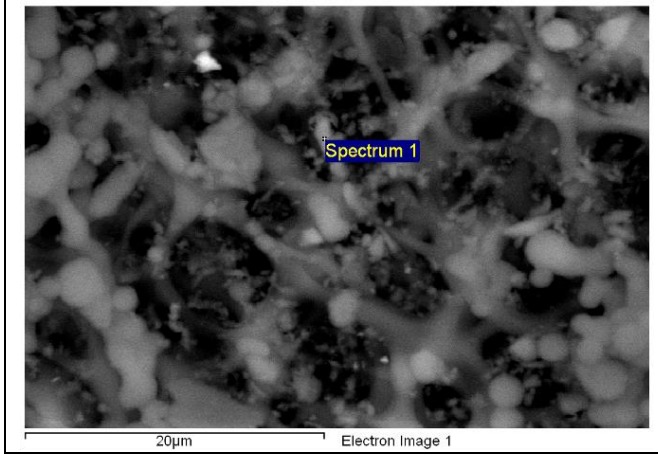


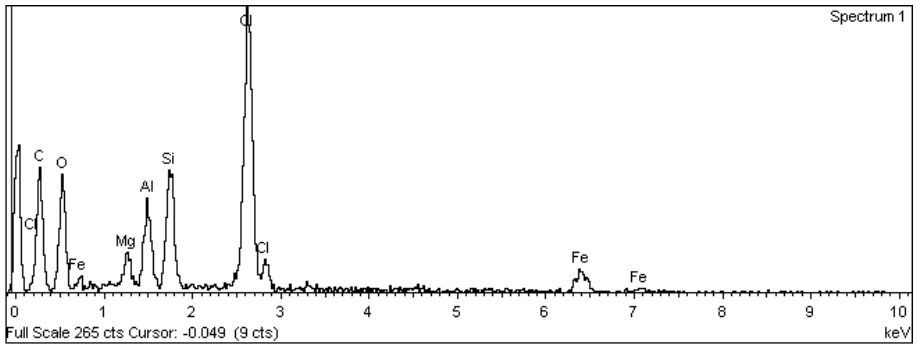
Site of interest 7



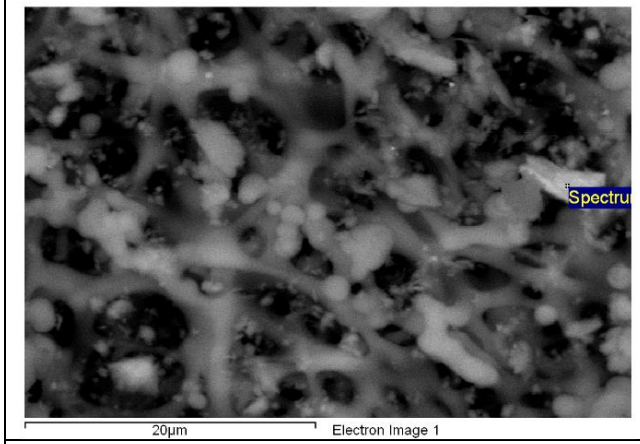


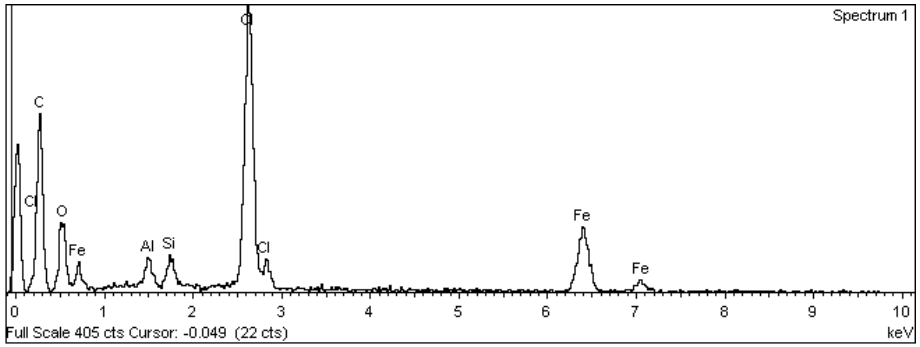
Site of interest 8



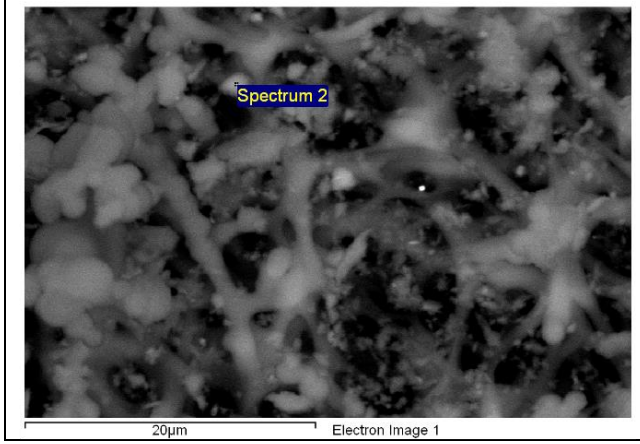


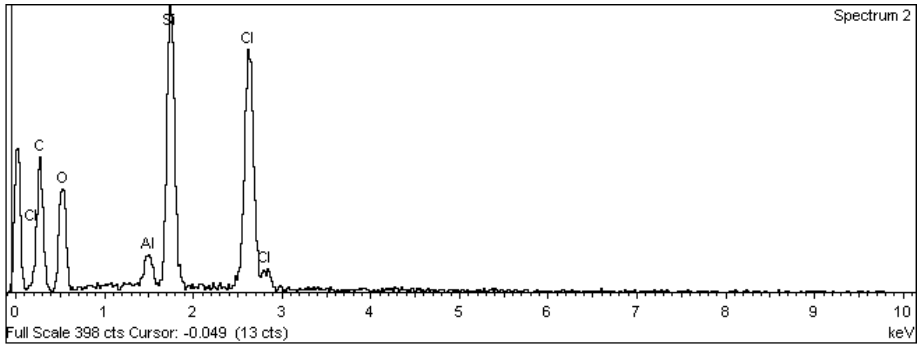
Site of interest 9



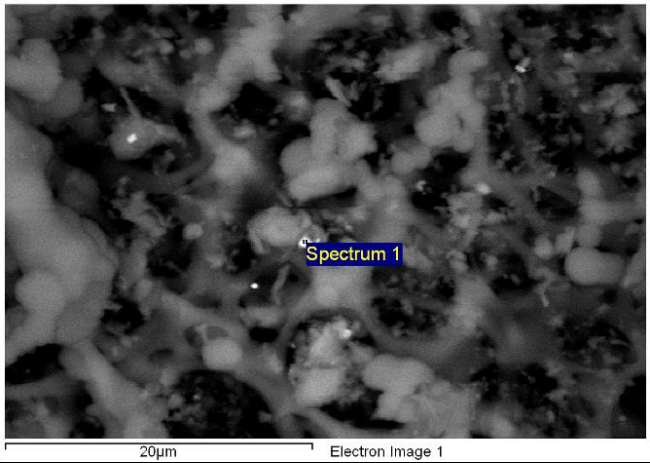


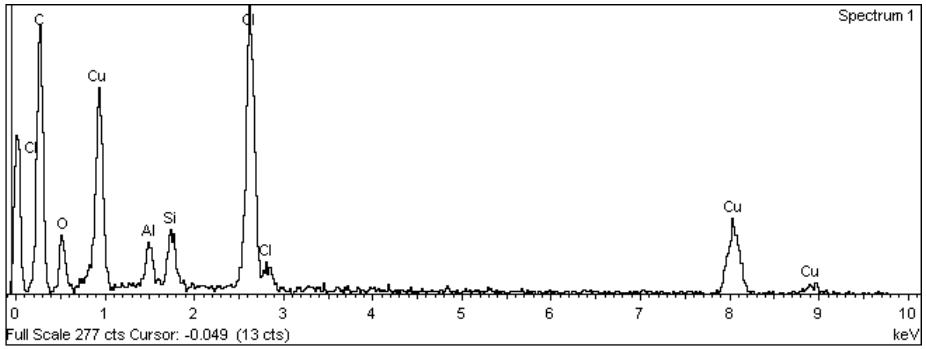
Site of interest 10



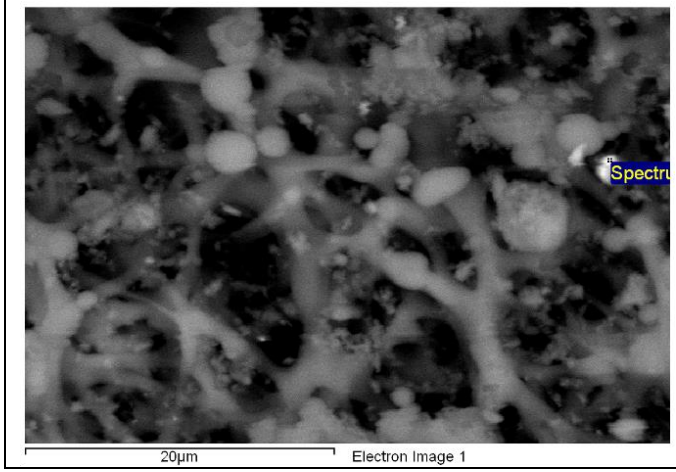


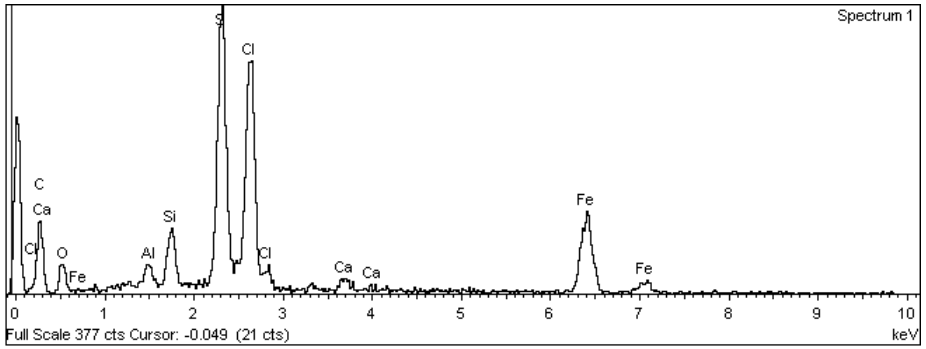
Site of interest 11



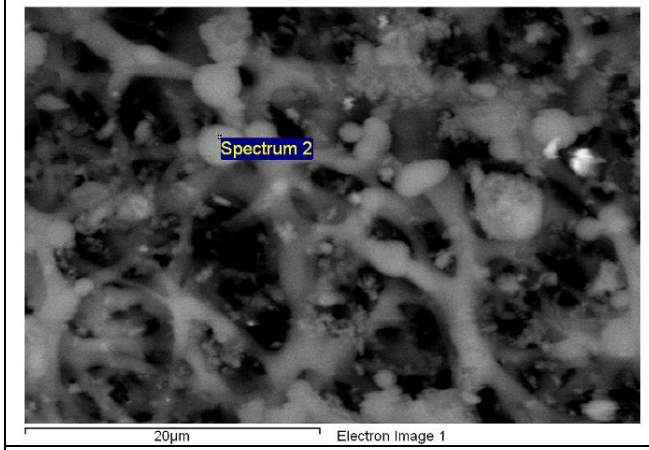


Site of interest 12

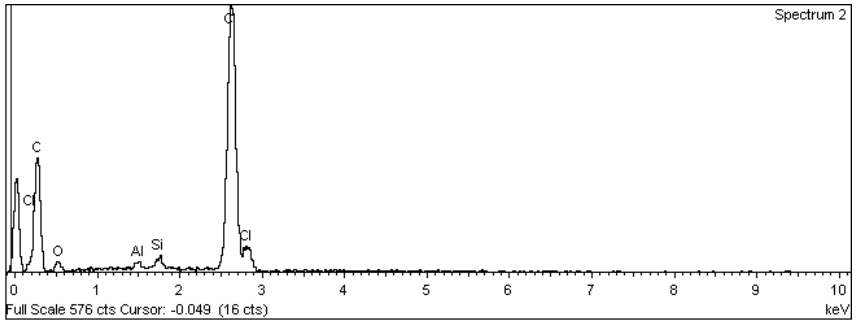




Site of interest 13



I19 EM micrograph images for F6725

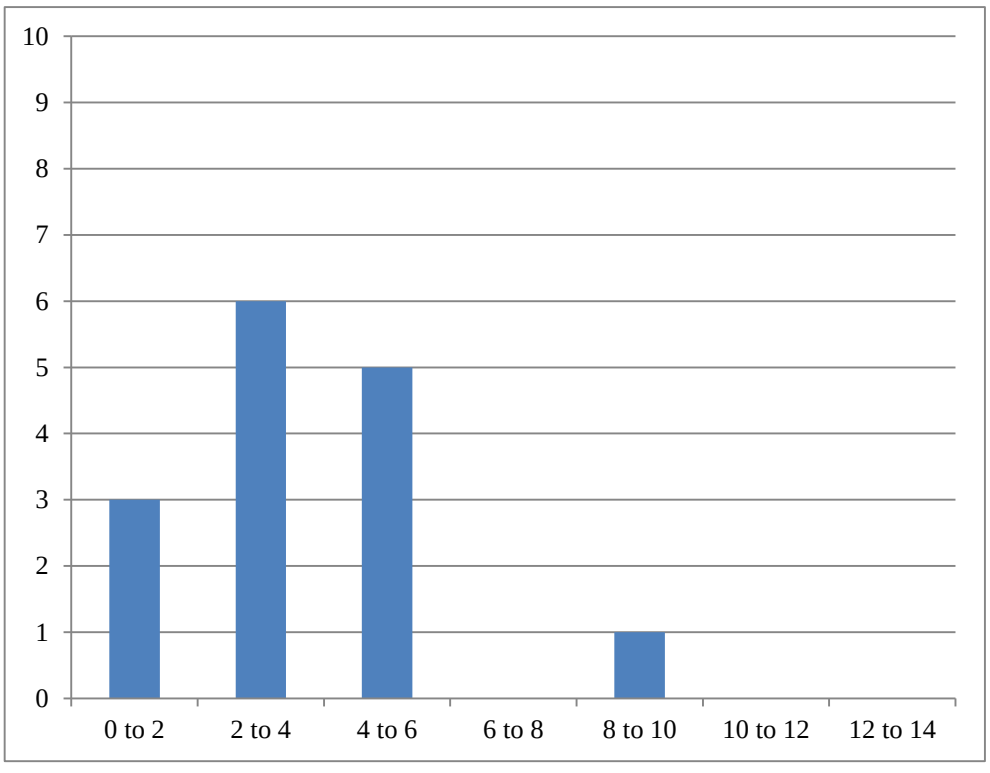


Site of interest 13

I20 Elemental spectrums for F6725

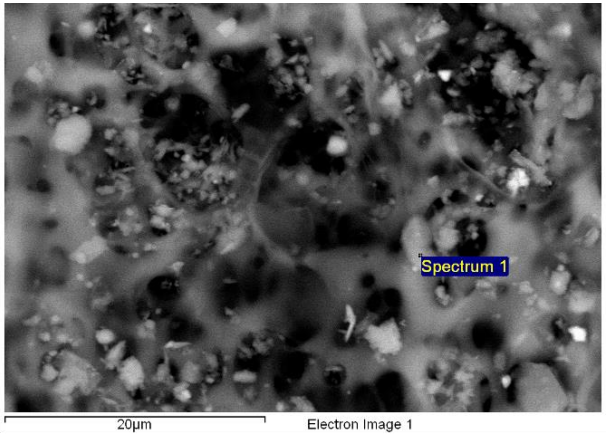
I21 Elemental scan for F4999

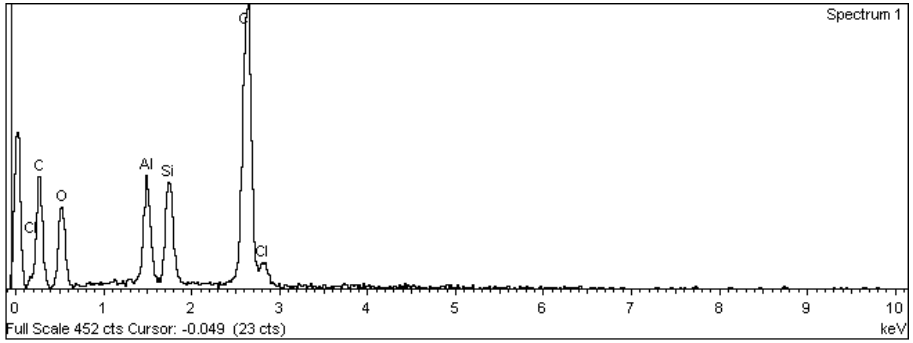
Fibre #	Image/Field #	Diameter (μm)	Major Elements	Minor Elements
1	1/1	7.5	O, Si, Al	K, Fe
2	2/1	1.0	O, Fe	Si, Al
3	2/2	2.9	O, Si	Fe, Al, K
4	3/1	2.6	O, Si	Al, K, Na
5	4/1	4.7	O, Si	Al
6	5/1	2.1	O, Si	Al
7	5/2	5.6	O, Si	Al, Ca
8	5/3	2.3	O, S, Fe	Si, Al, K
9	6/1	5.0	O, Si, Al	K, Fe
10	7/1	7.5	O, Si, Fe	Al
11	8/1	5.1	O, Si	Al, K, Fe
12	9/1	3.3	O, Si	Al, K, Fe, Na, Mn
13	10/1	2.4	O, Si	F, Fe, Al, K
14	12/1	2.9	O, S, Fe	Si, Al
15	13/1	22.5	O, Si	Al



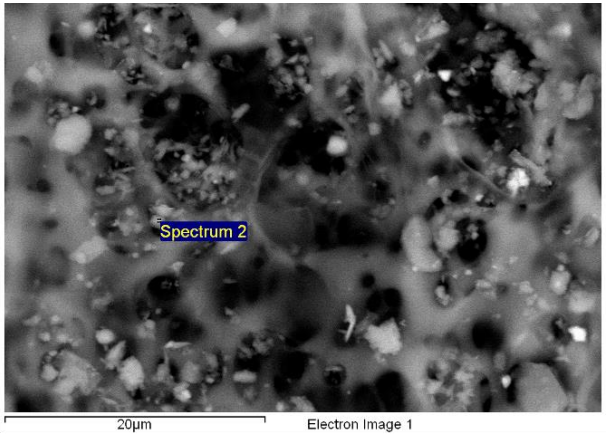
I22: Particle size distribution for F4999

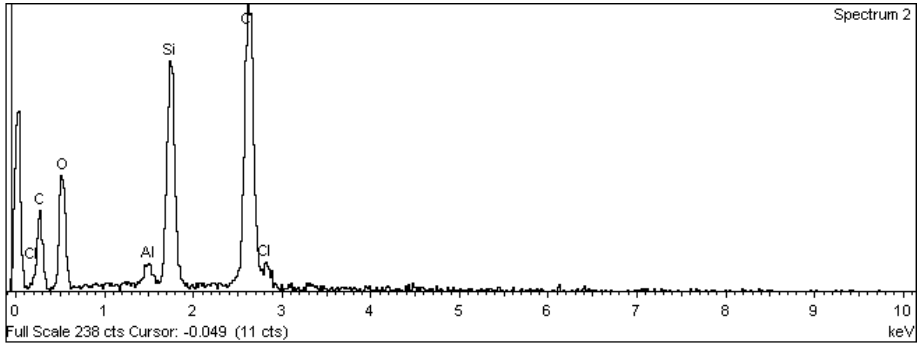
F4999



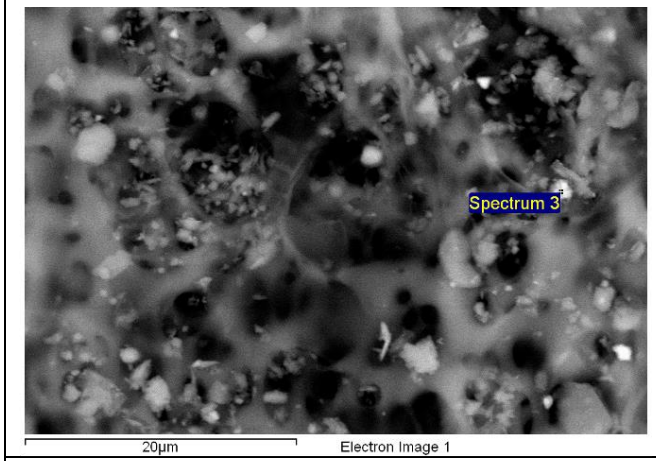


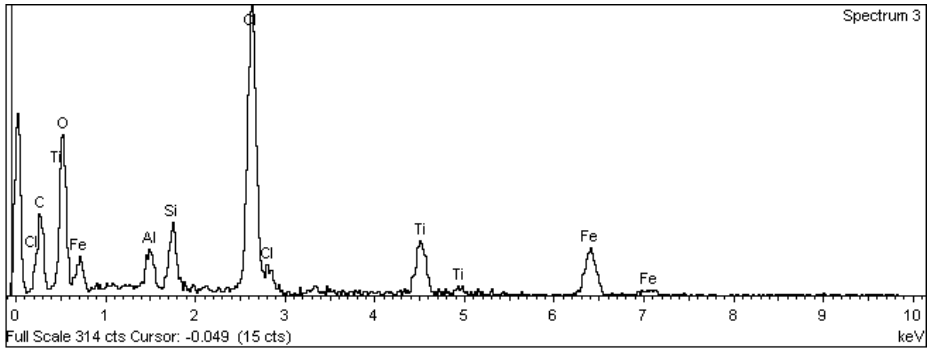
Site of interest 1



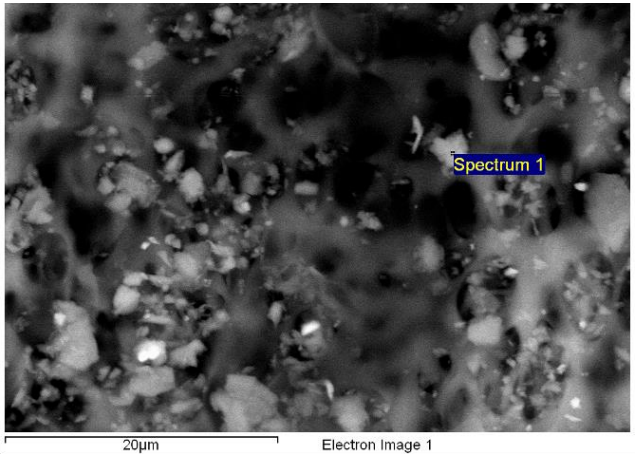


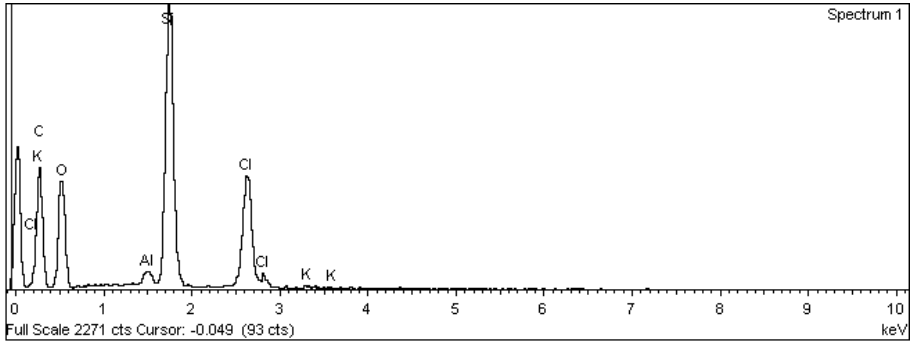
Site of interest 1



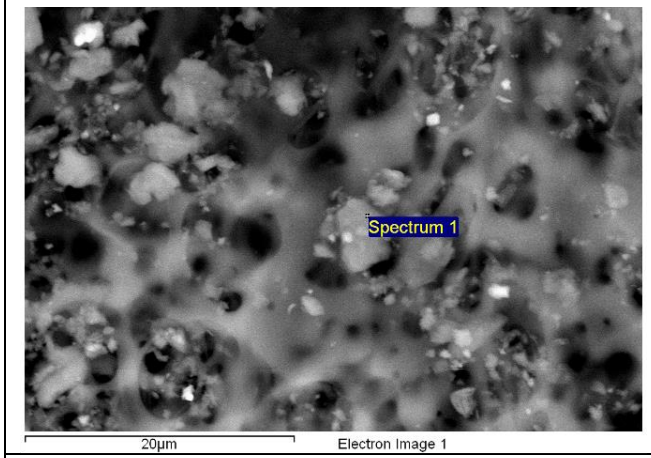


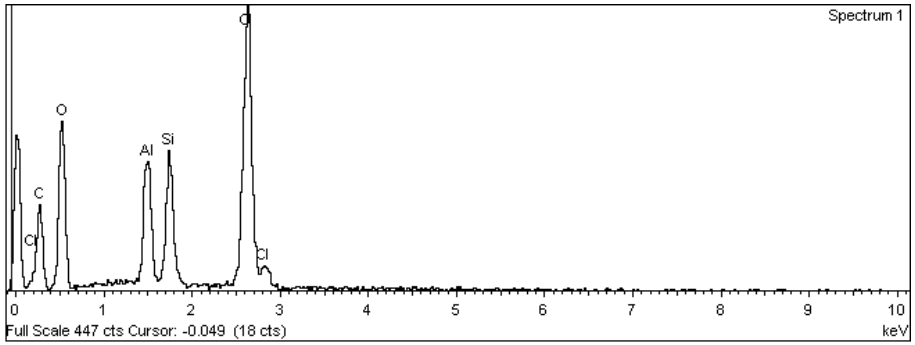
Site of interest 1



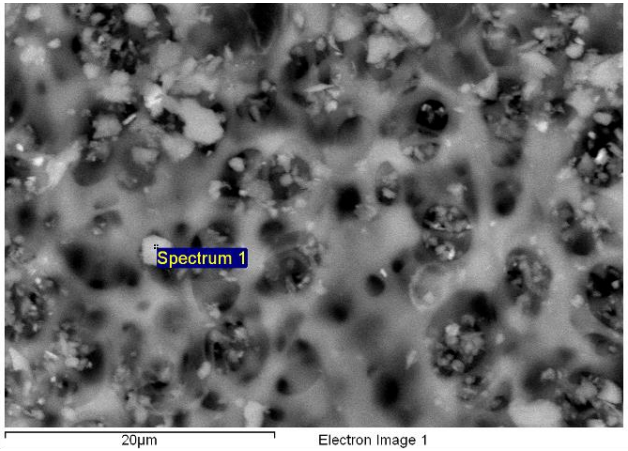


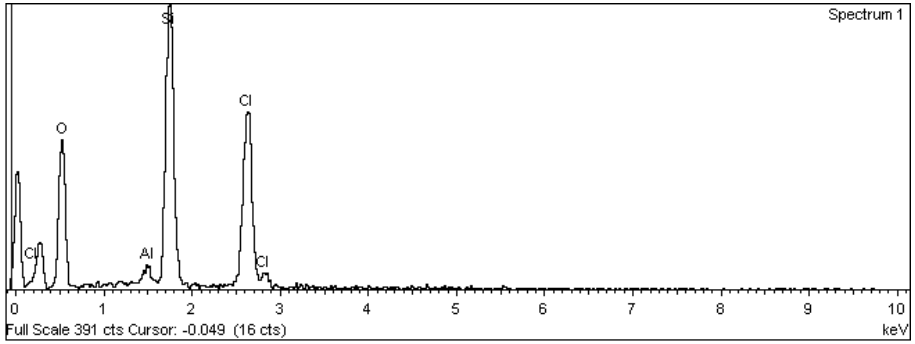
Site of interest 2



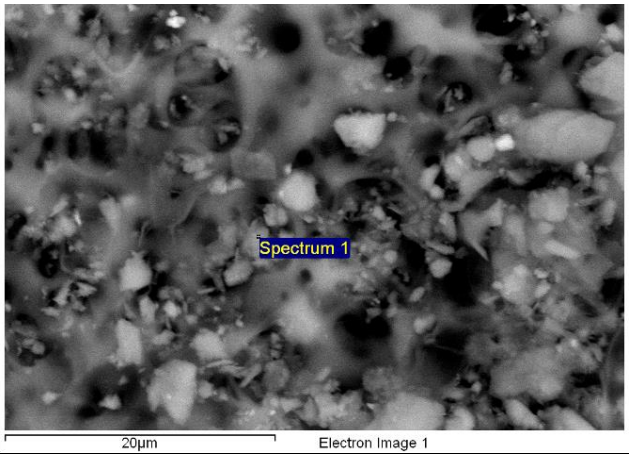


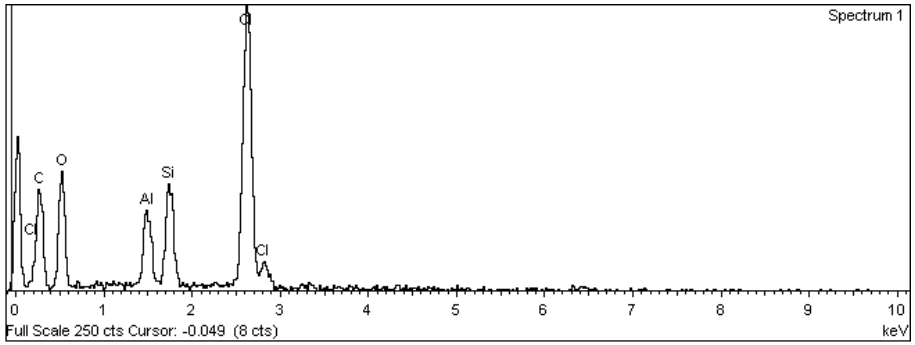
Site of interest 3



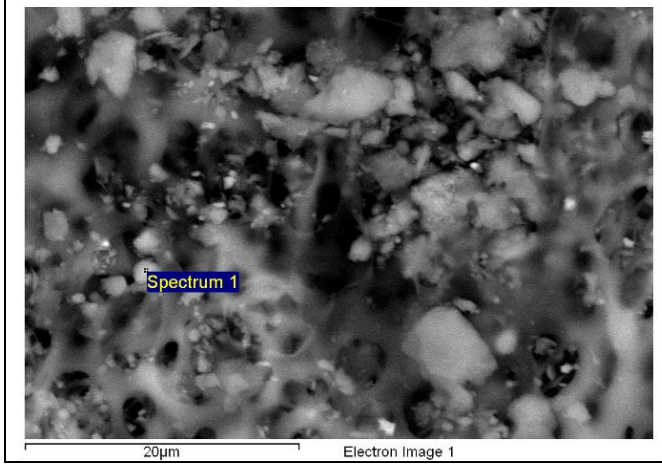


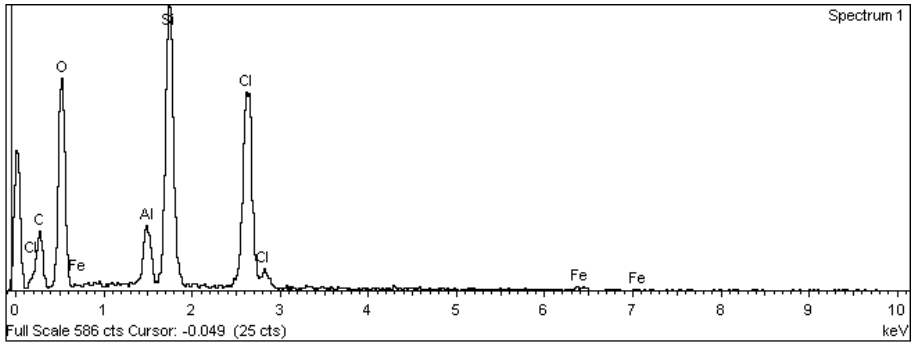
Site of interest 4



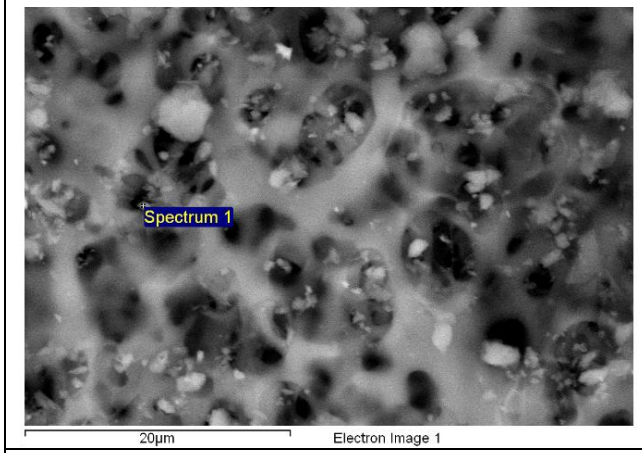


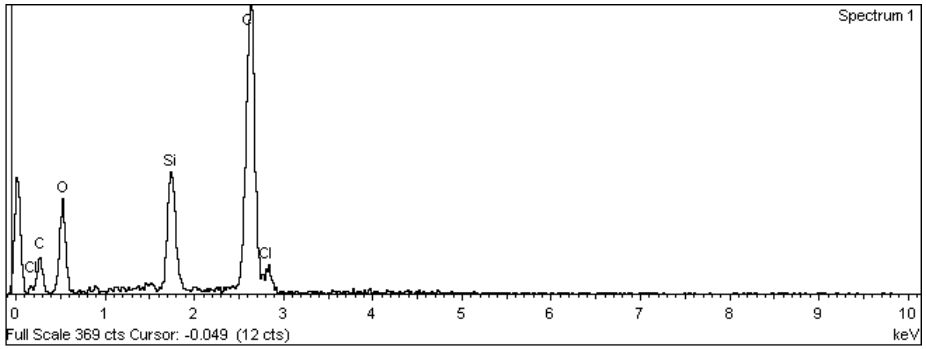
Site of interest 5



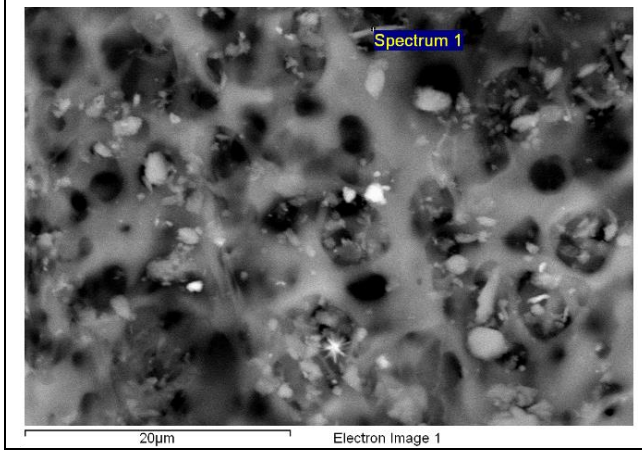


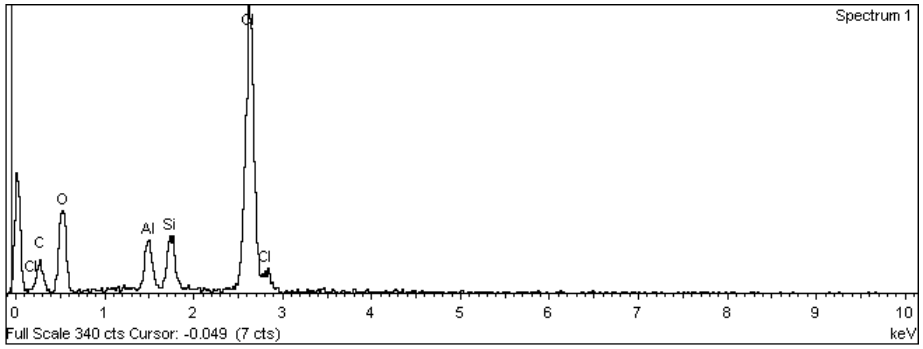
Site of interest 6



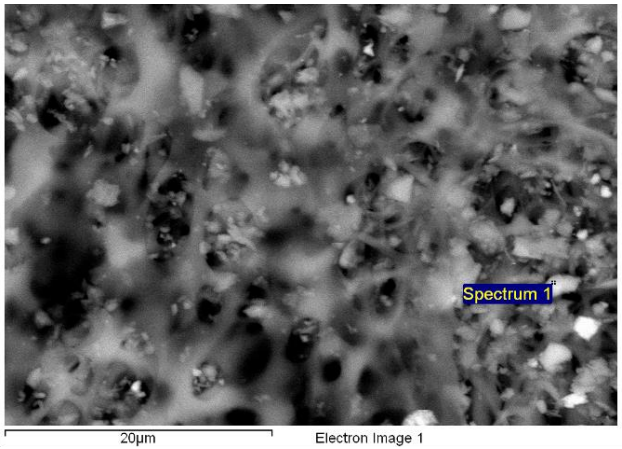


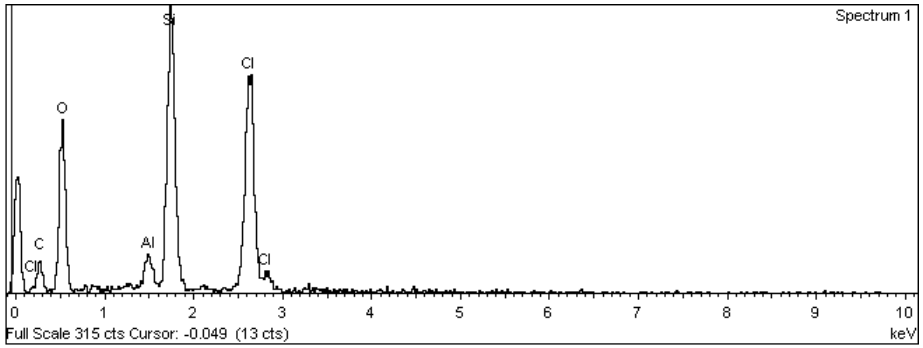
Site of interest 7



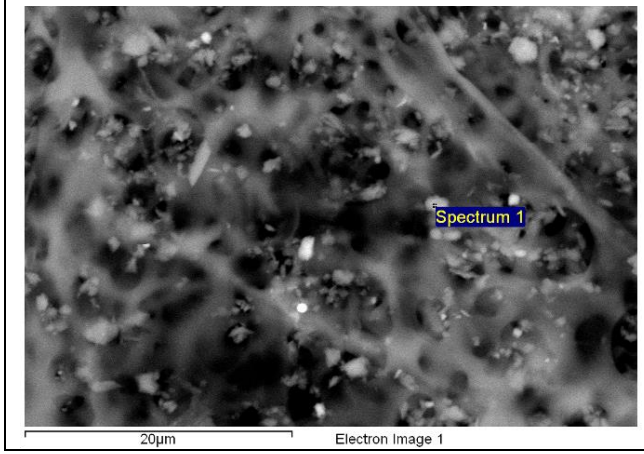


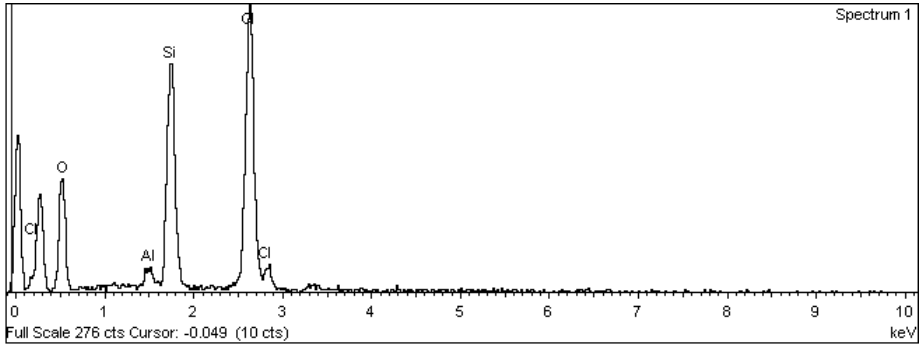
Site of interest 8



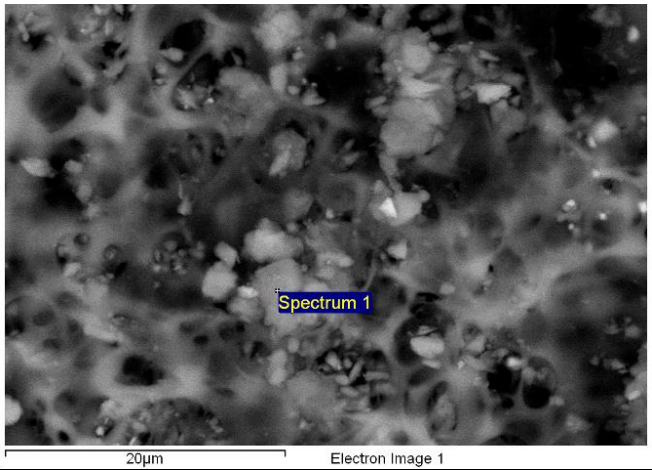


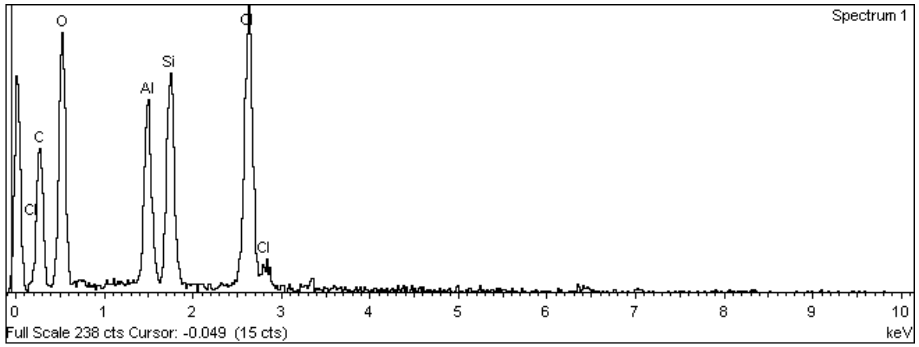
Site of interest 9



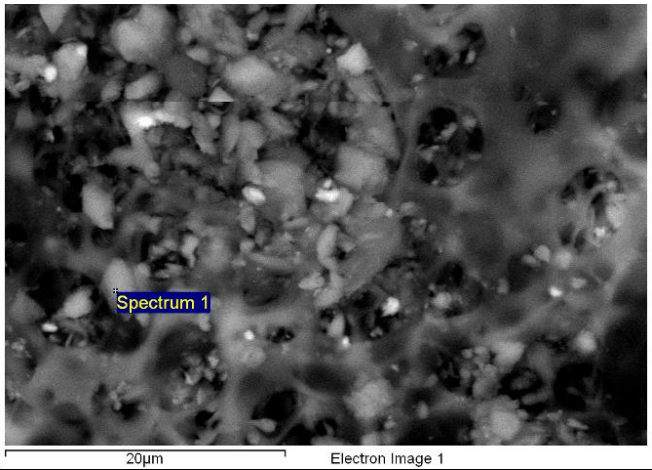


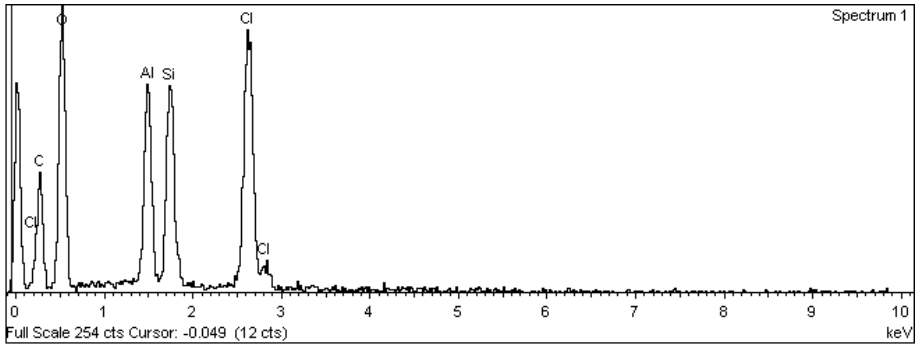
Site of interest 10



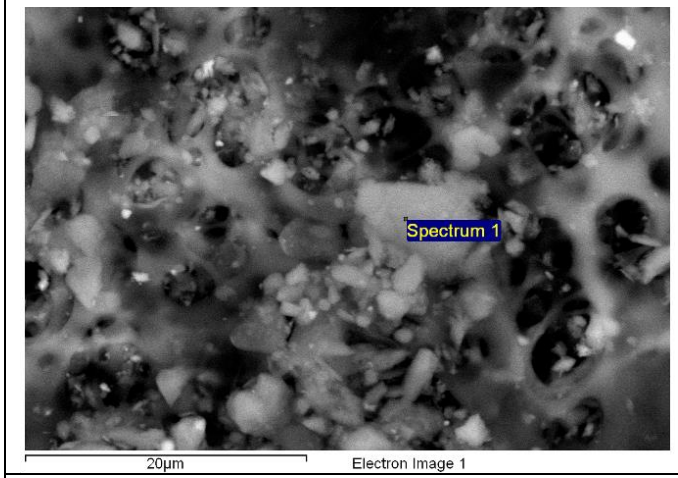


Site of interest 11

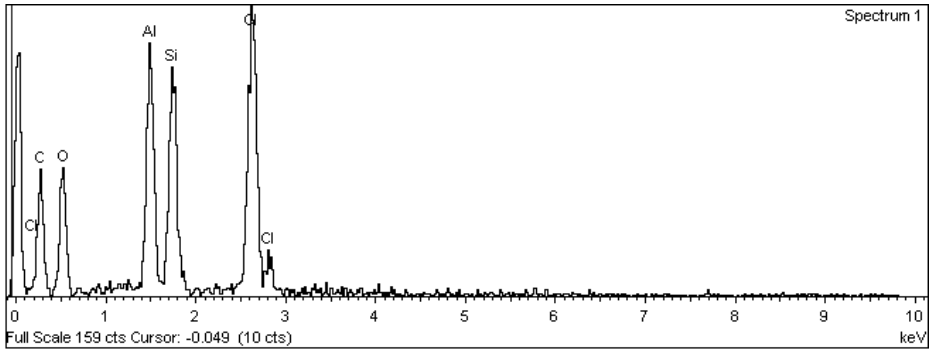




Site of interest 12



I23 EM micrograph images for F4999

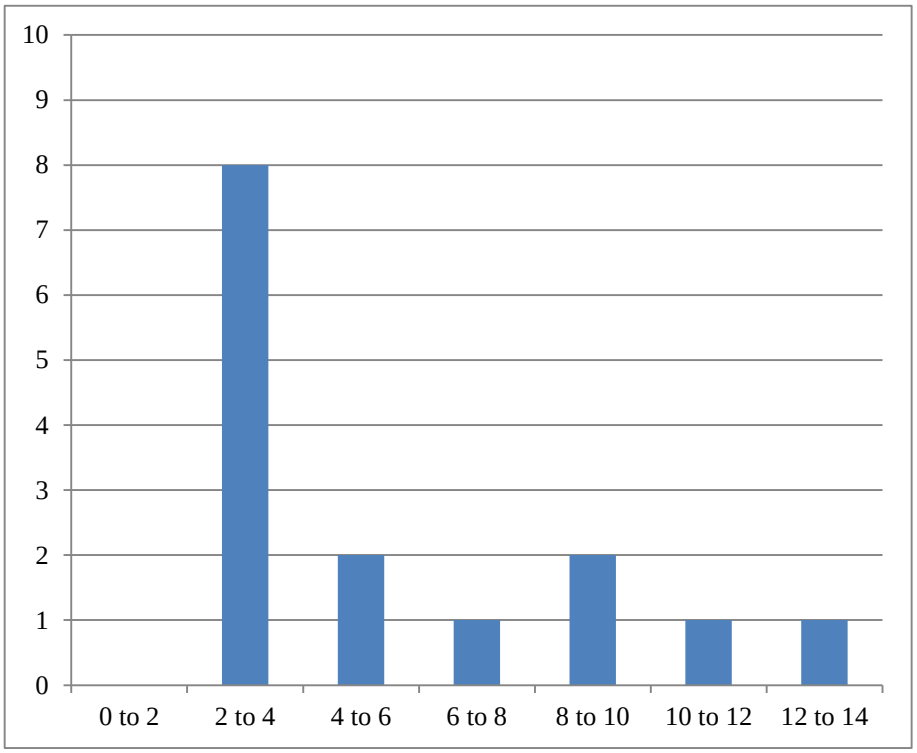


Site of interest 13

I24 Elemental spectrums for F4999

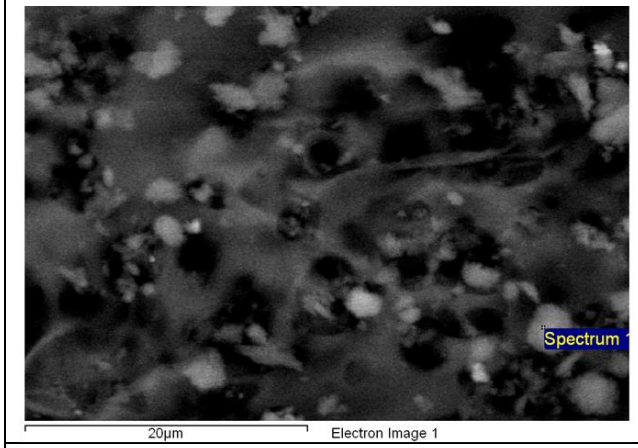
I25 Elemental scan for F6727

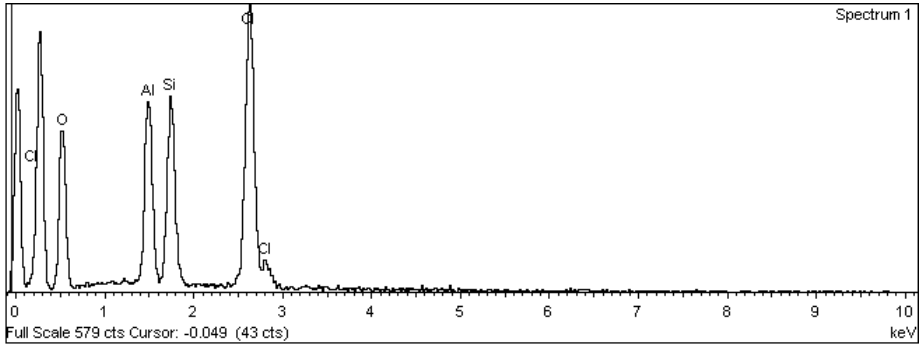
Particle #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	1/1	3.0	O, Si, Al	-
2	3/1	3.1	O, Si, Al	-
3	4/1	12.2	O, Si	Mg, Al, Fe, Ca
4	5/1	10.9	O, Si	Al, Ca, Na
5	6/1	6.4	O, Si	Al
6	7/1	9.2	O, Ti	Si, Al
7	9/1	8.9	O, Si. Al	-
8	13/1	2.7	O, Si. Al	Fe, K
9	14/1	4.8	O, Si. Al	Fe
10	15/1	2.6	O, Si	Al
11	16/1	3.4	O, Si, Al	-
12	17/1	2.8	O, Si	Al
13	20/1	3.5	O, Si, Al	Fe
14	21/1	3.6	O, Si, Al	-
15	23/1	5.1	O, Si, Al	Fe



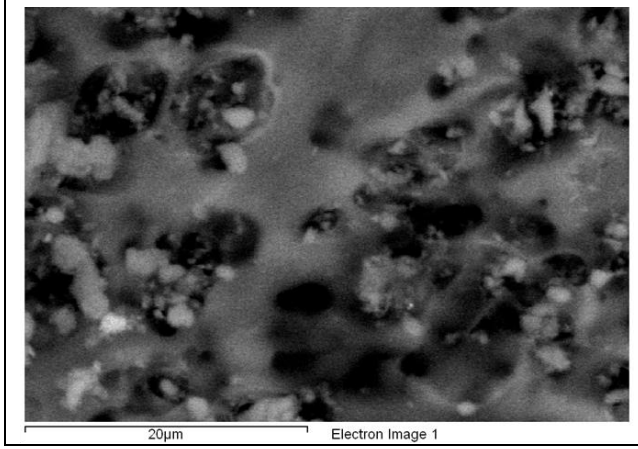
I26: Particle size distribution for F6727

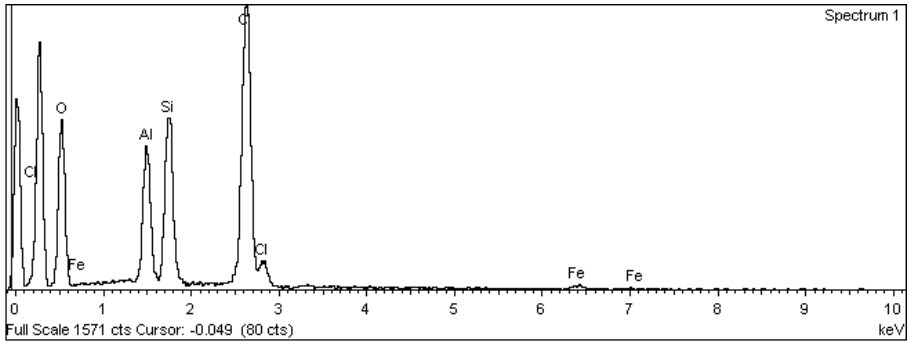
F6727



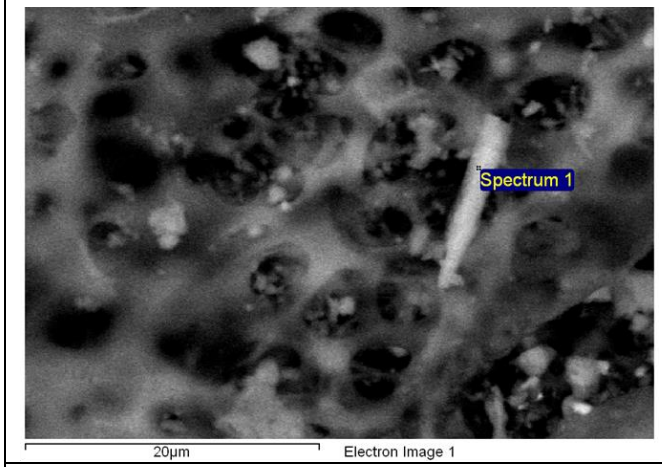


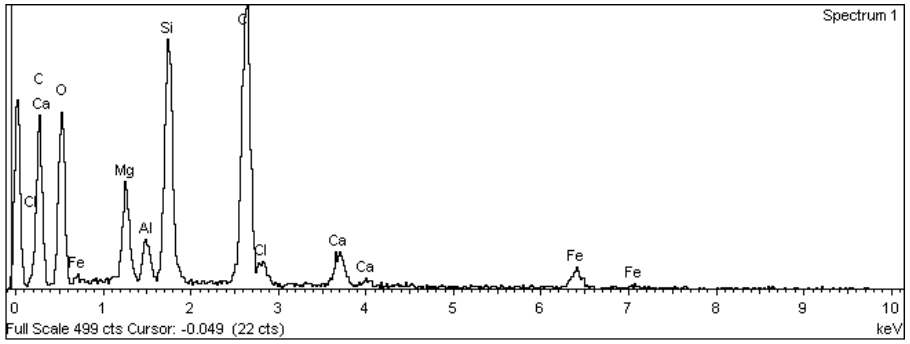
Particle 1



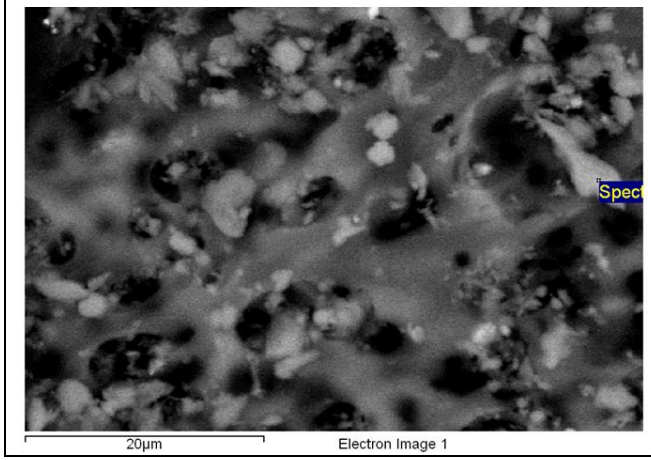


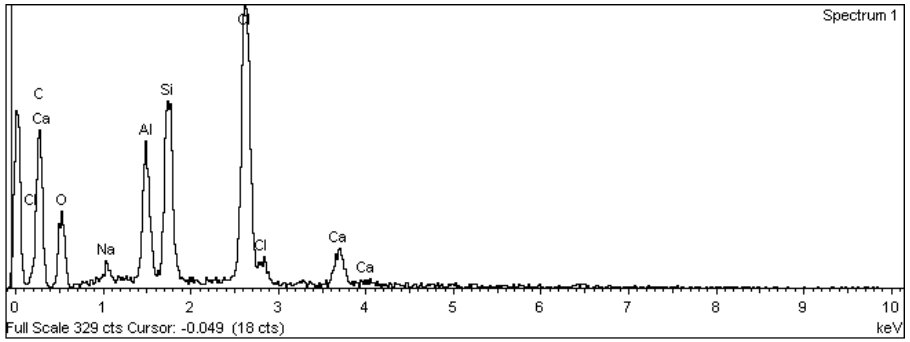
Particle 2



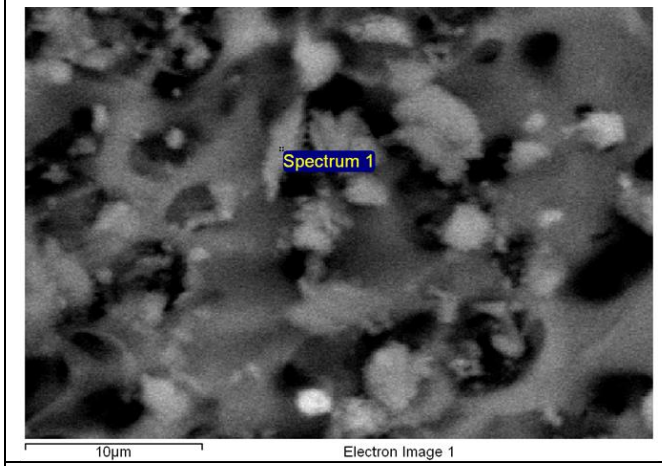


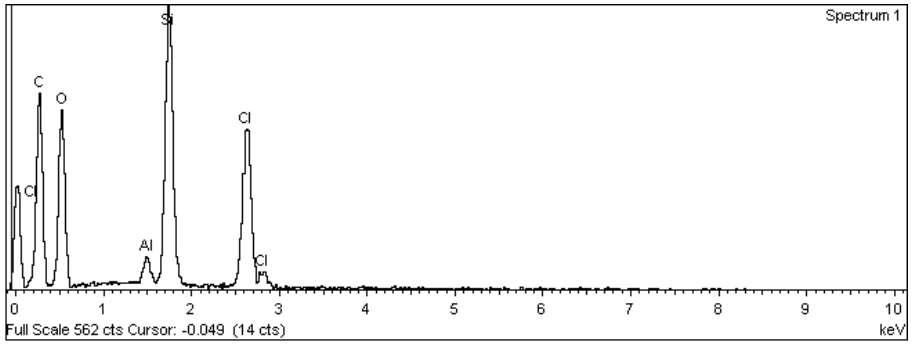
Particle 3



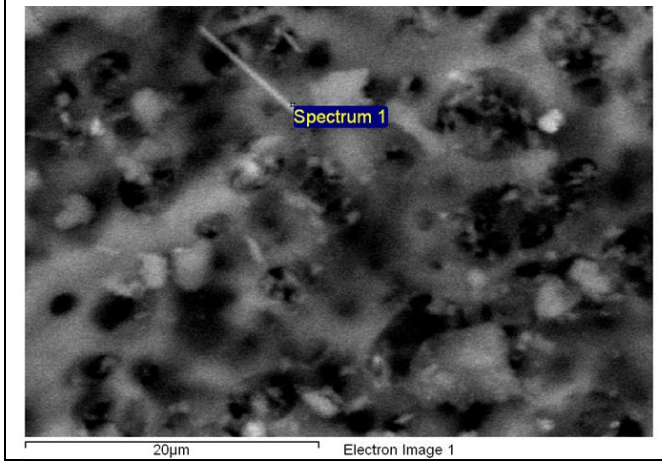


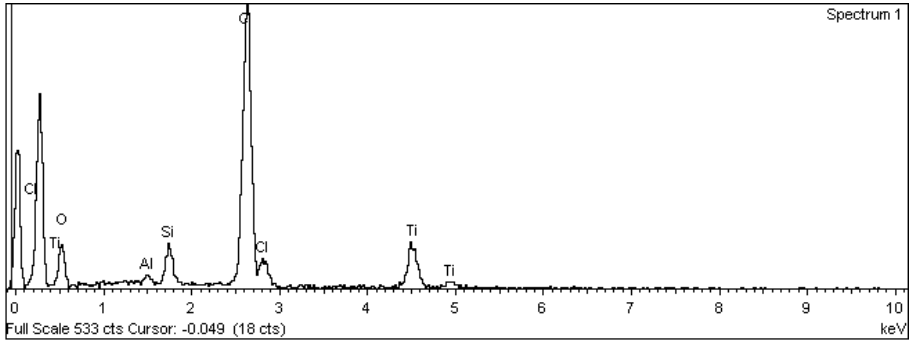
Particle 4



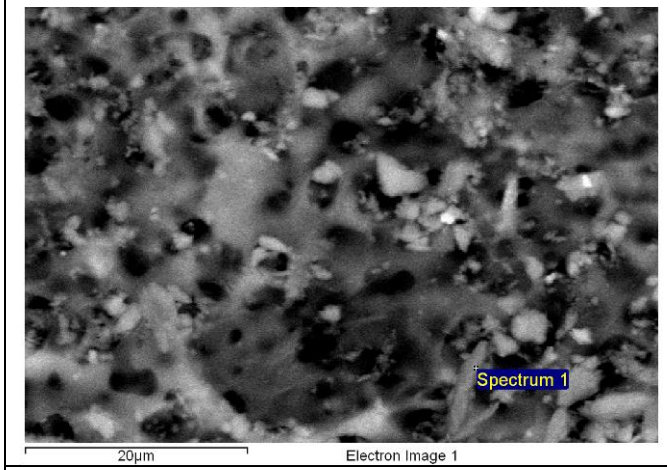


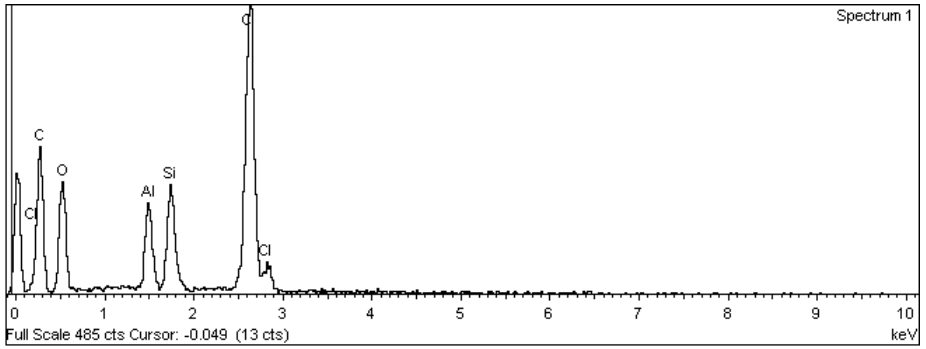
Particle 5



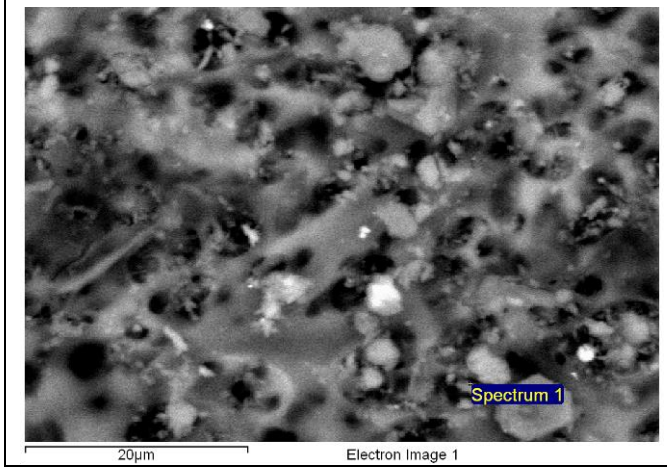


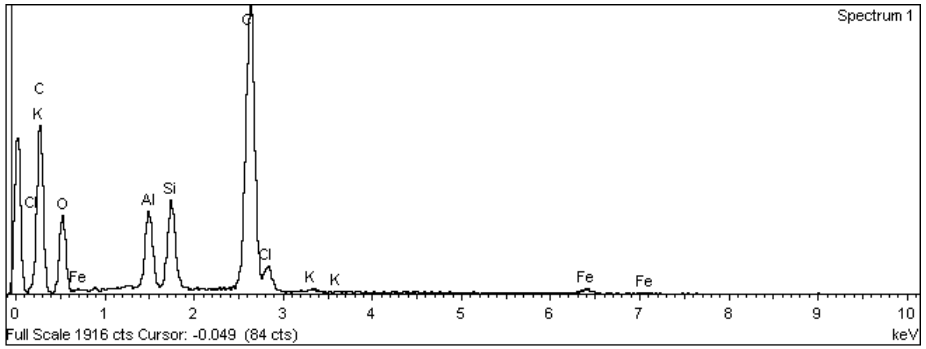
Particle 6



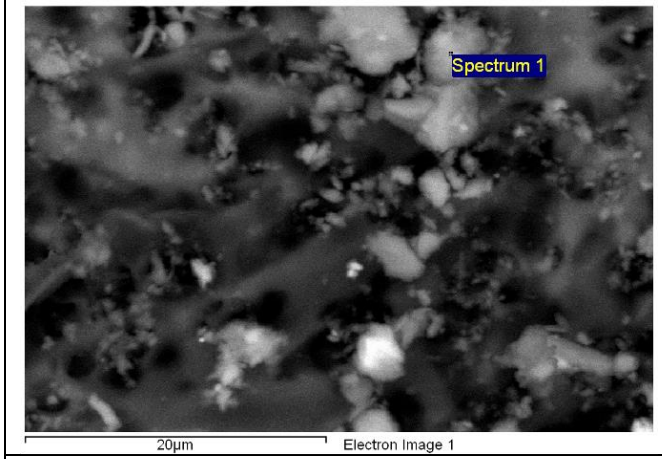


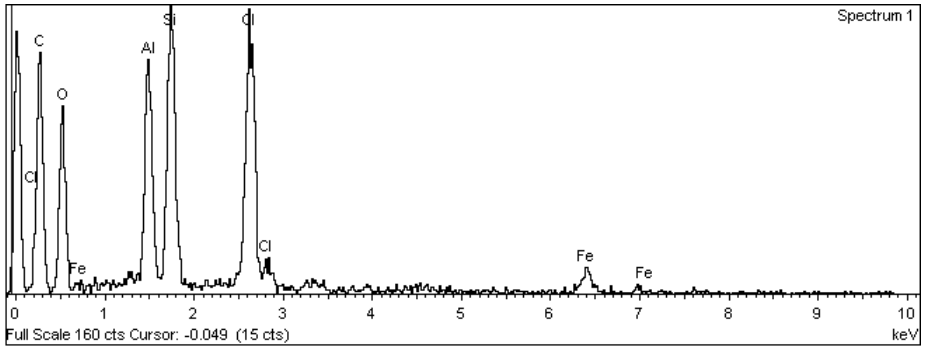
Particle 7



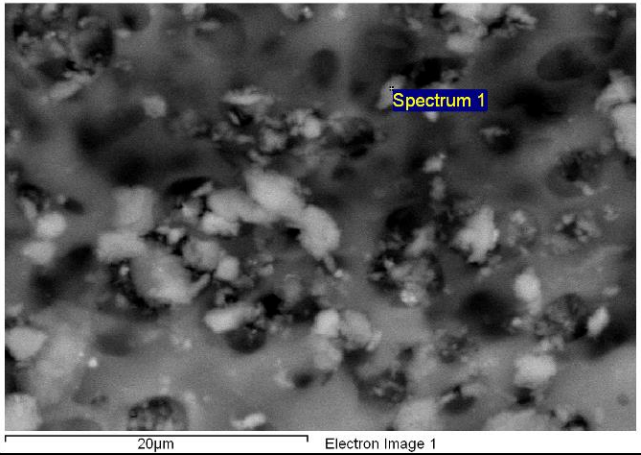


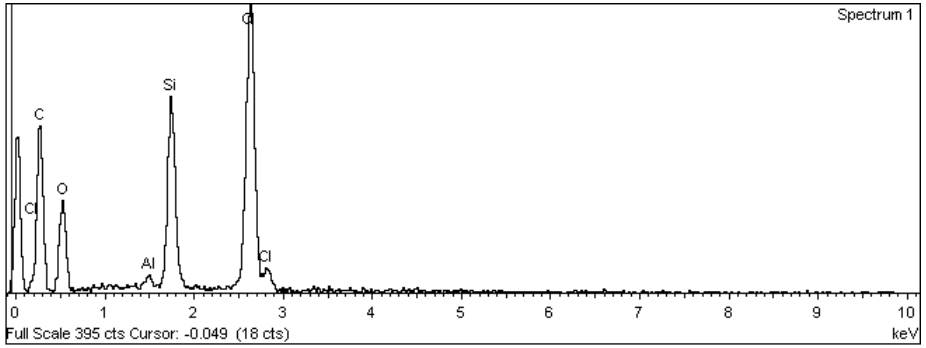
Particle 8



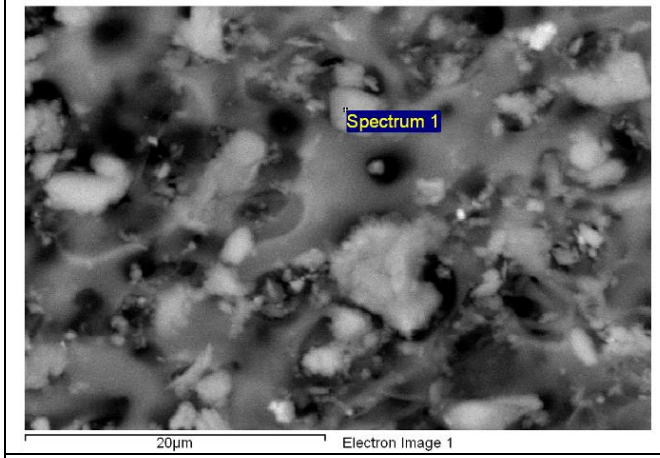


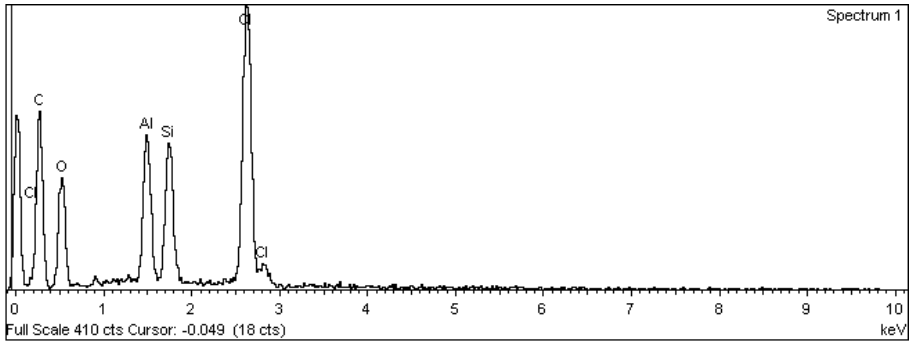
Particle 9



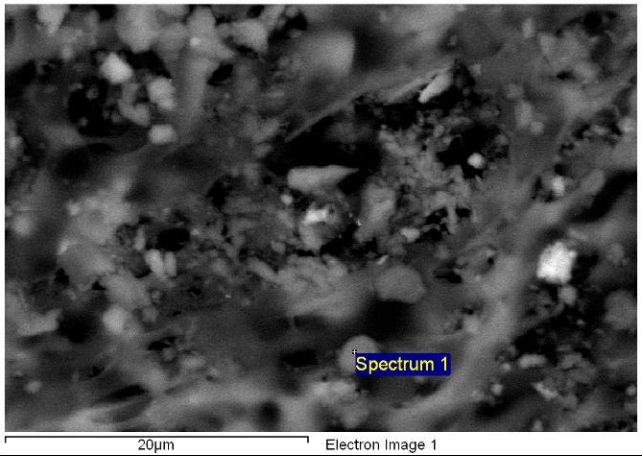


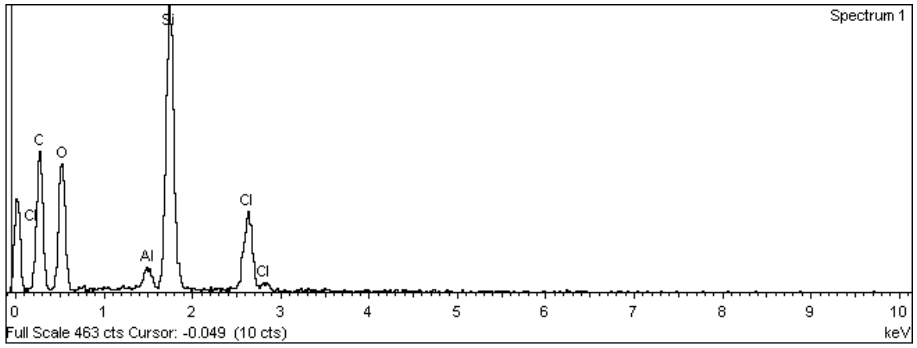
Particle 10



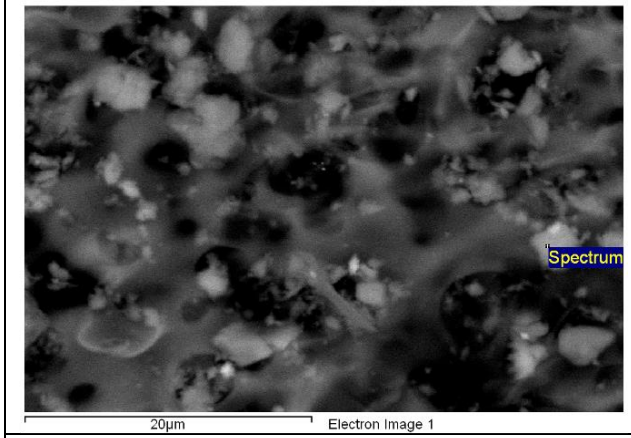


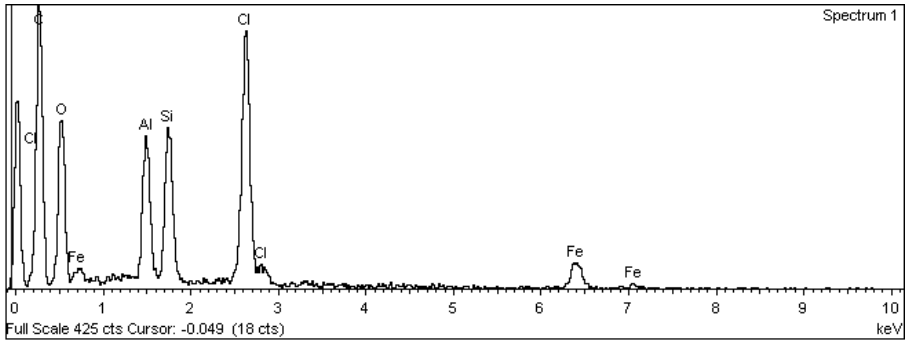
Particle 11



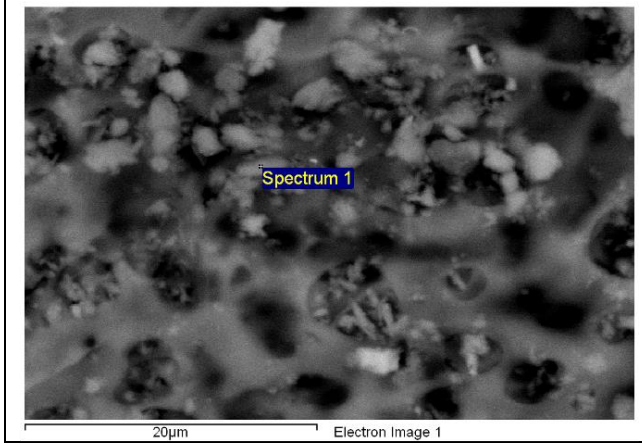


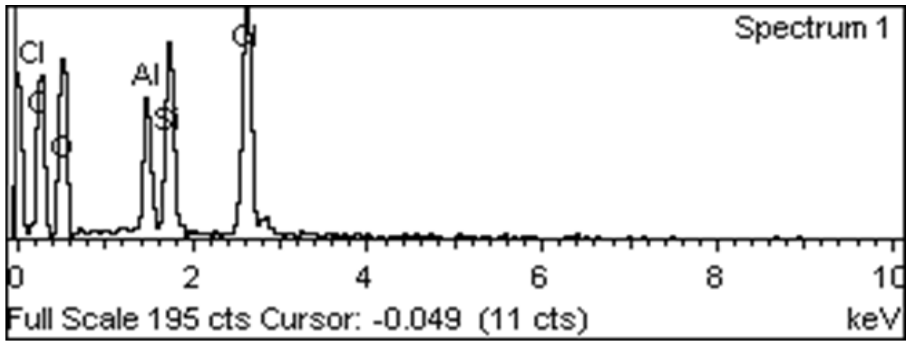
Particle 12



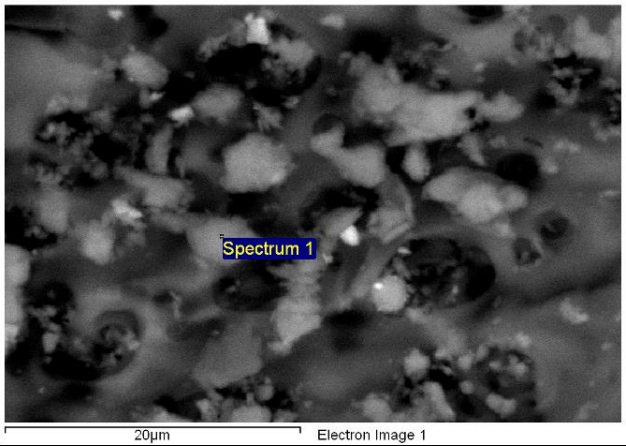


Particle 13

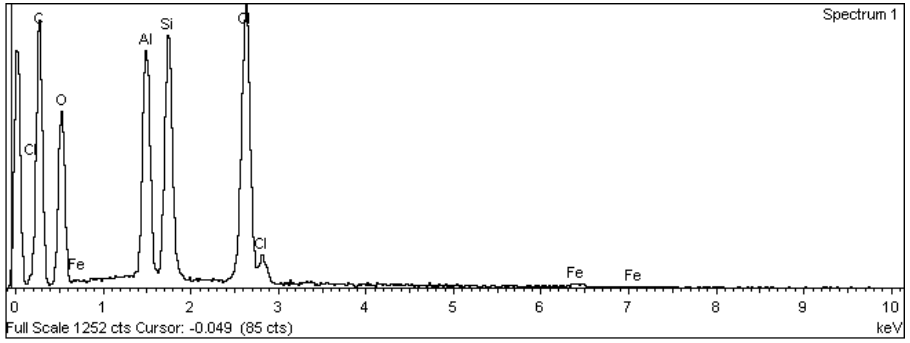




Particle 14



I27 EM micrograph images for F6727

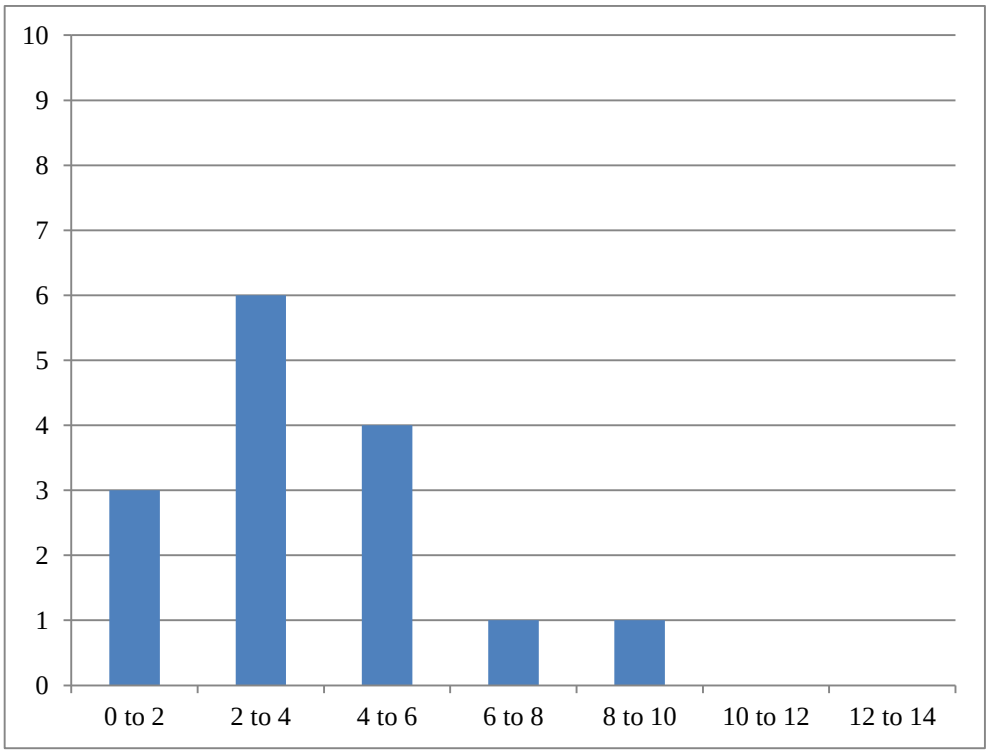


Particle 15

I28 Elemental spectrums for F6727

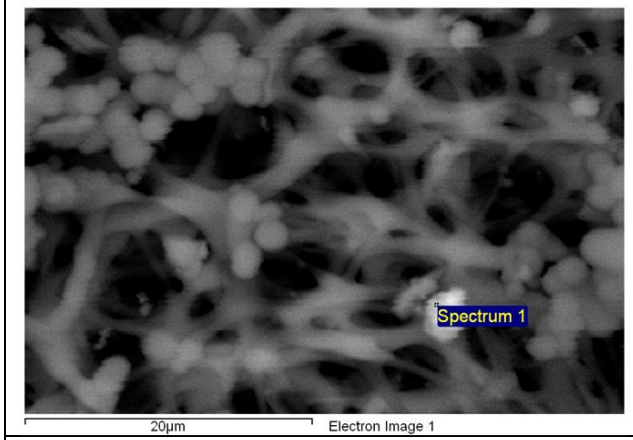
I29 Elemental scan for F5243

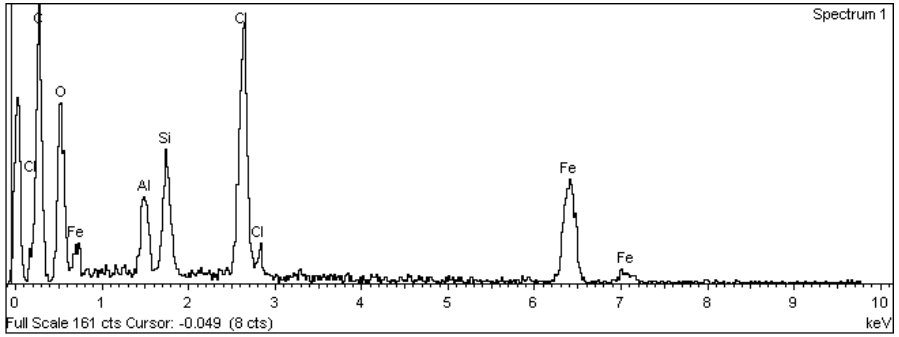
Particle #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	2/1	3.8	O, Fe	Si, Al
2	3/1	4.4	Cu	-
3	4/1	4.4	O, Si	-
4	5/1	6.4	O, Cu	-
5	6/1	2.3	O, Cu	Si
6	7/1	2.5	O, Cu	-
7	7/2	1.2	O, Cu	-
8	8/1	2.8	O, Si, Al	-
9	9/1	4.4	O, Fe	Si, Al, Mn
10	10/1	9.7	O, Ti	Fe, Al, Si, Mg
11	11/1	2.6	O, Ba, S	Si
12	12/1	1.6	O, Al	P, Si
13	12/2	1.0	O, Fe	-
14	14/1	2.7	O, Fe	Si, Al, K
15	14/2	4.4	O, Fe	Si, Al, K



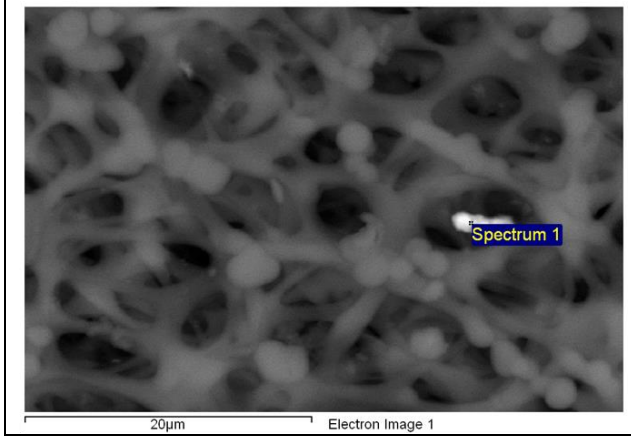
I30: Particle size distribution for F5243

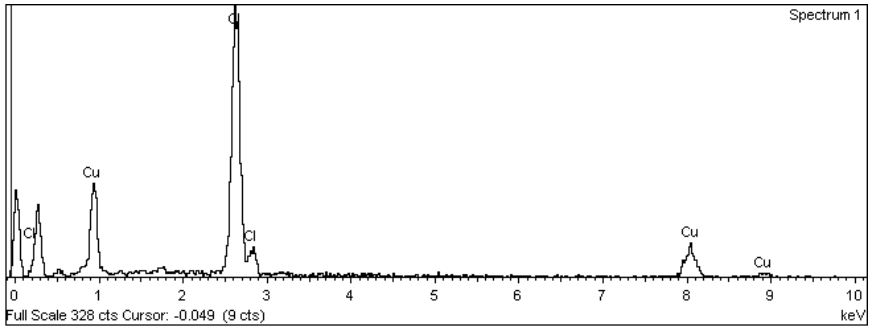
F5243



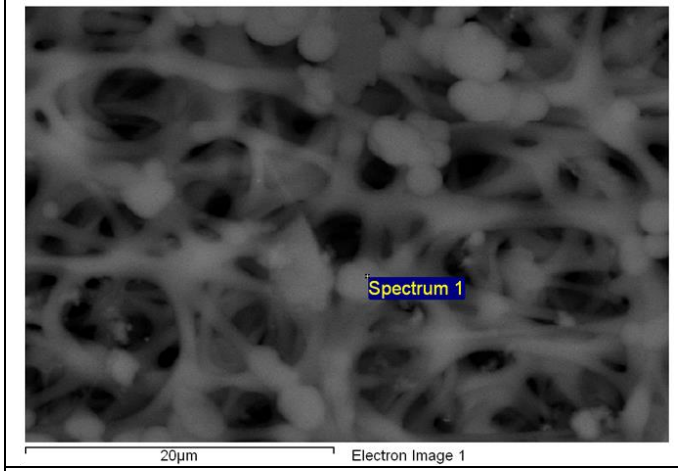


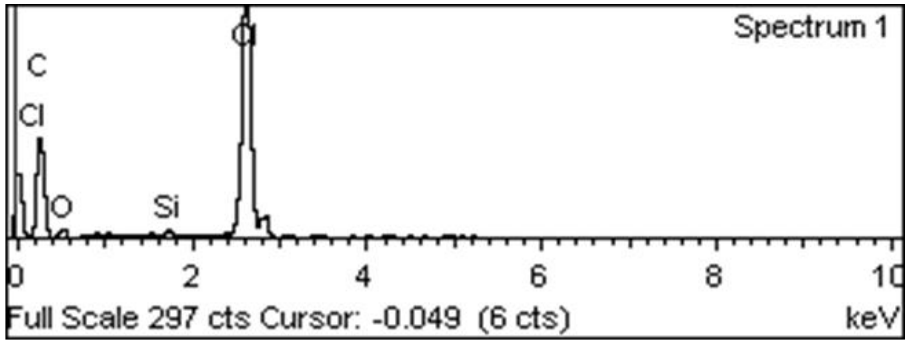
Site of interest 2



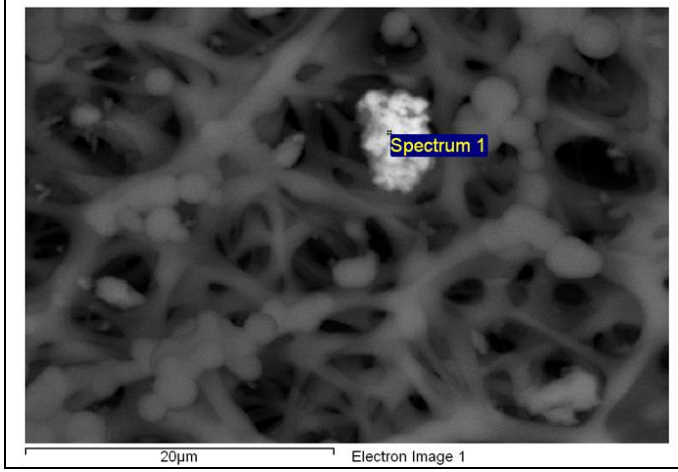


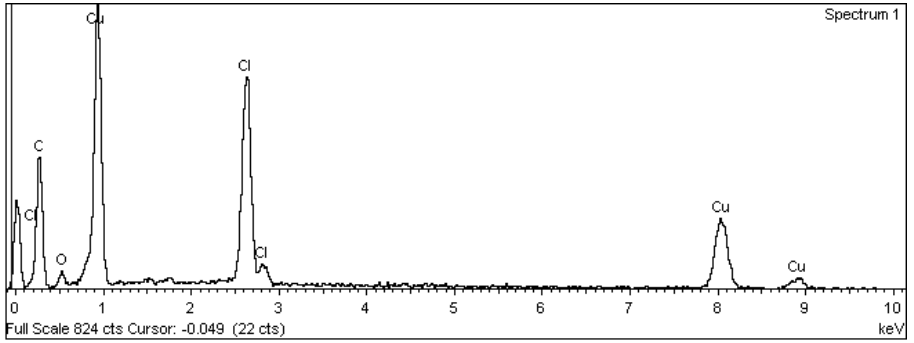
Site of interest 3



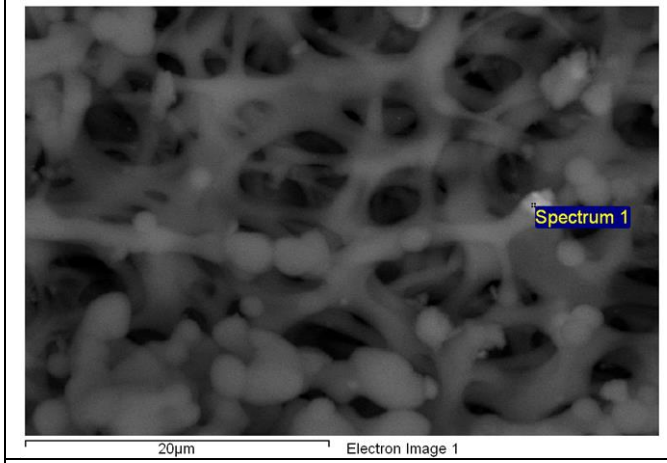


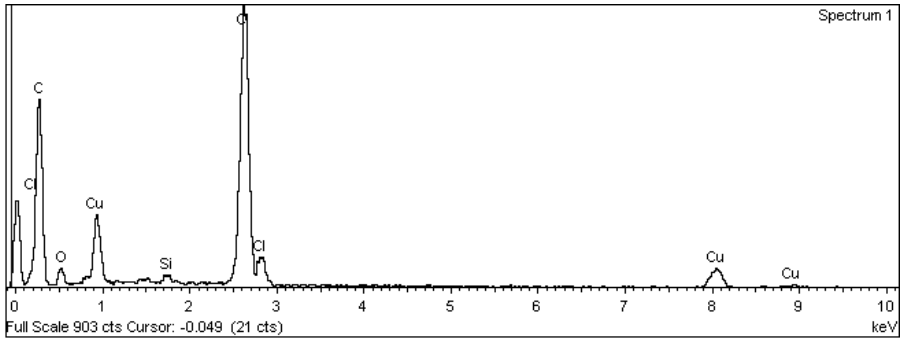
Site of interest 4



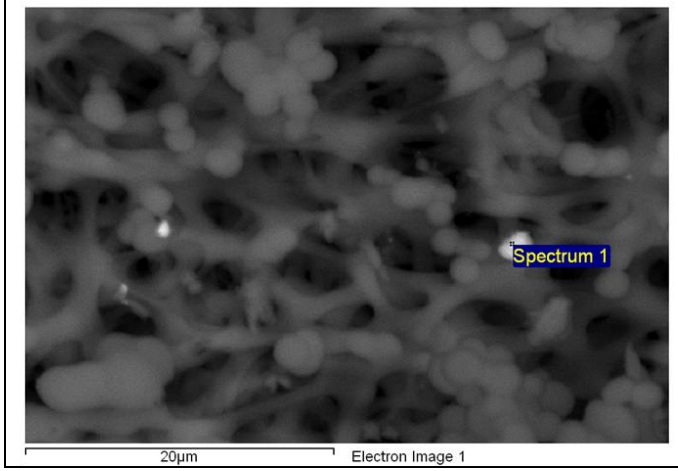


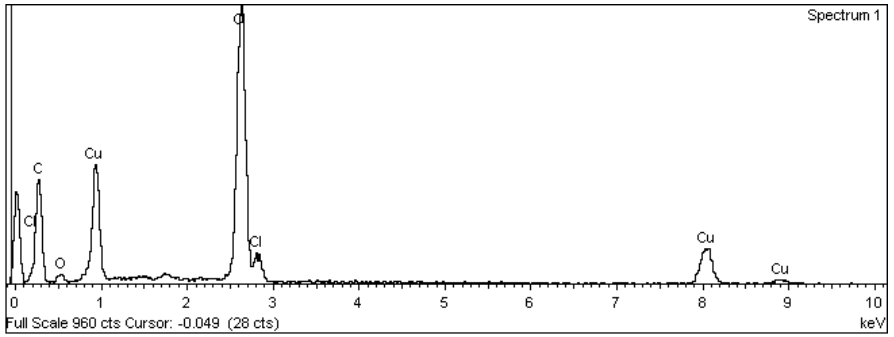
Site of interest 5



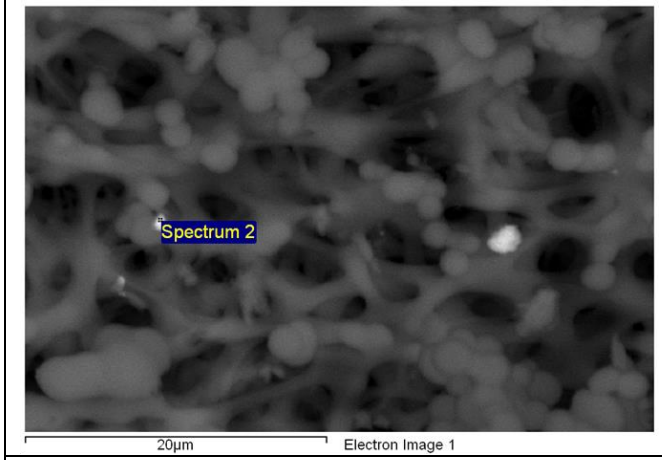


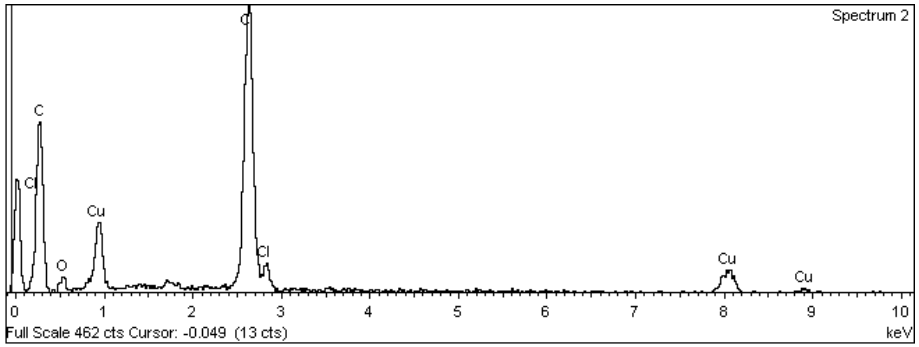
Site of interest 6



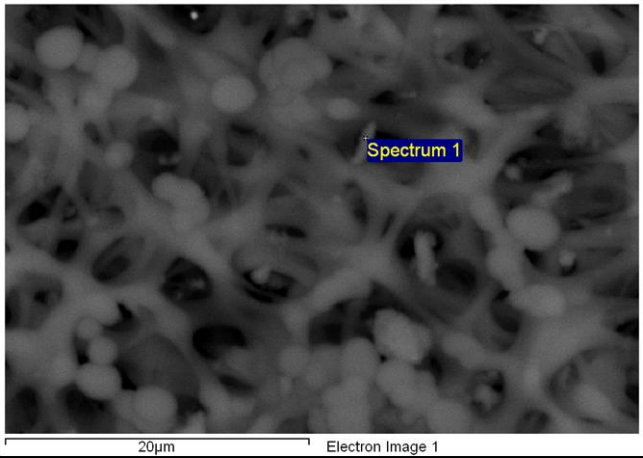


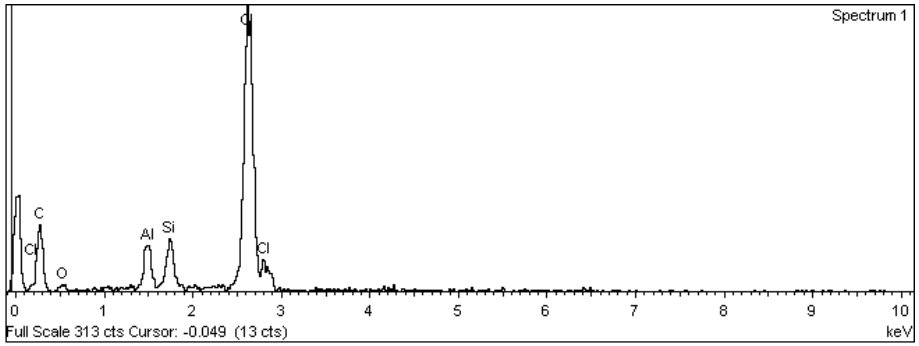
Site of interest 7



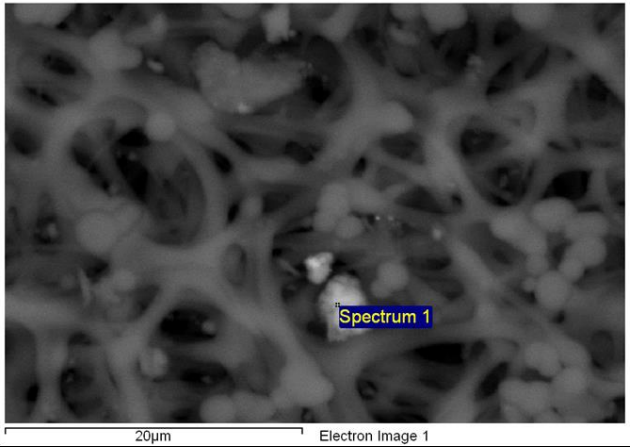


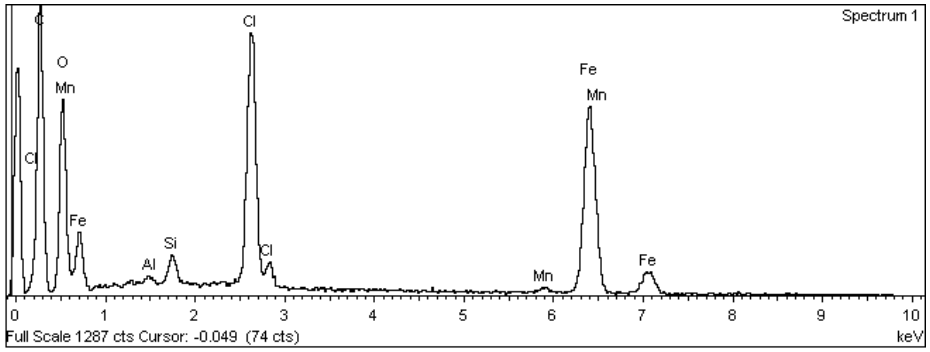
Site of interest 7



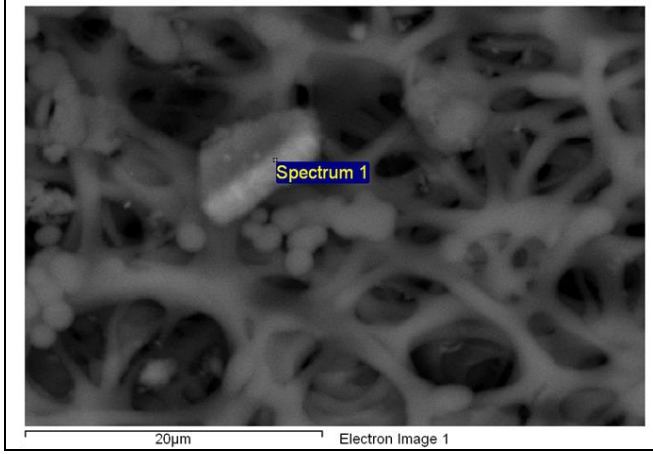


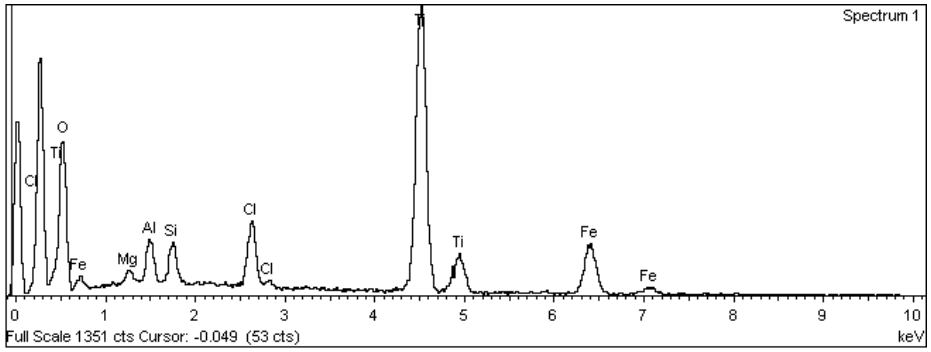
Site of interest 8



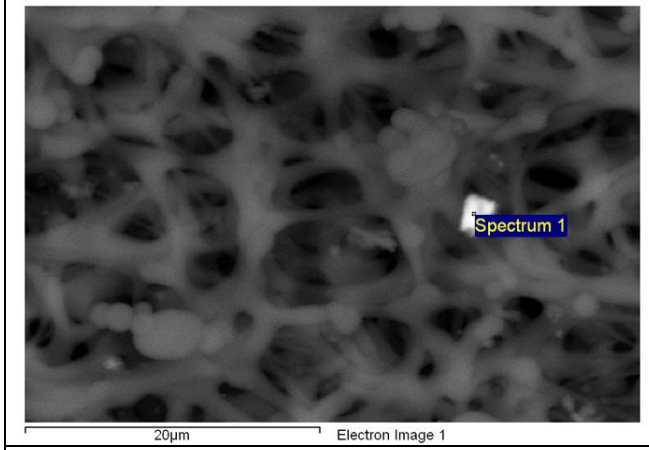


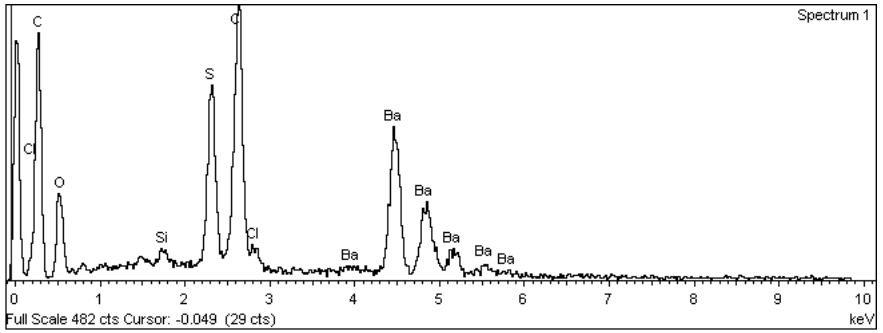
Site of interest 9



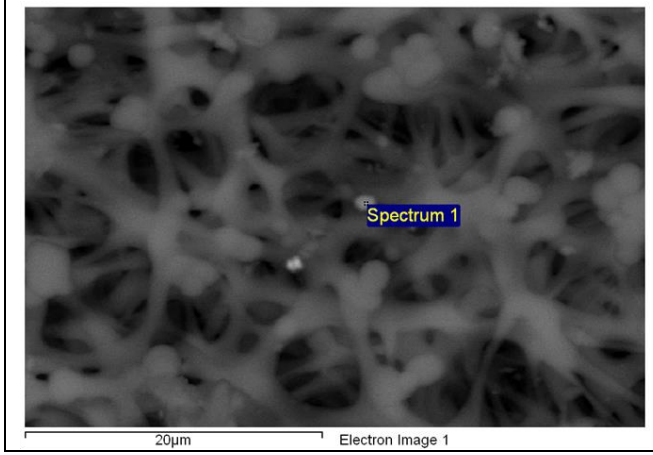


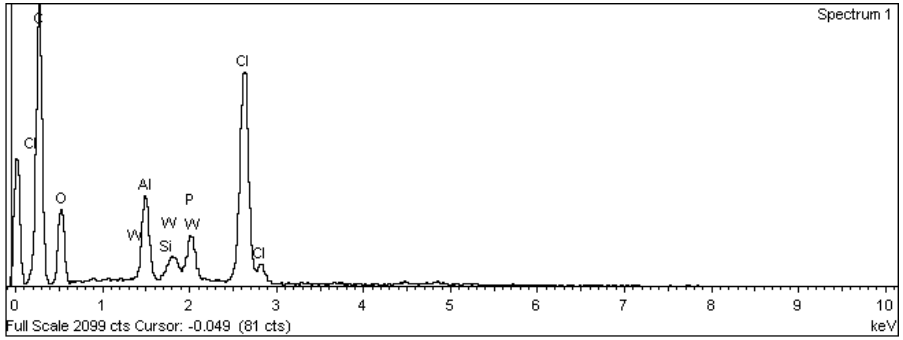
Site of interest 10



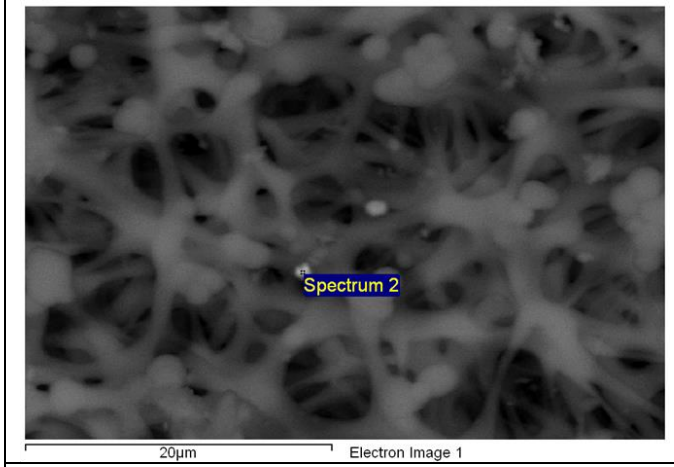


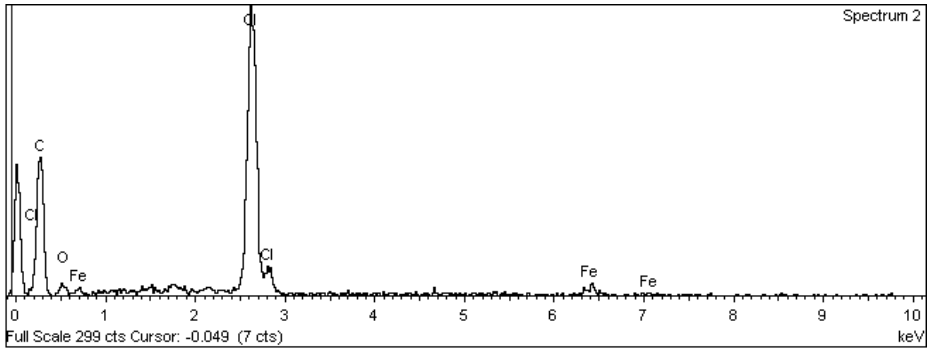
Site of interest 11



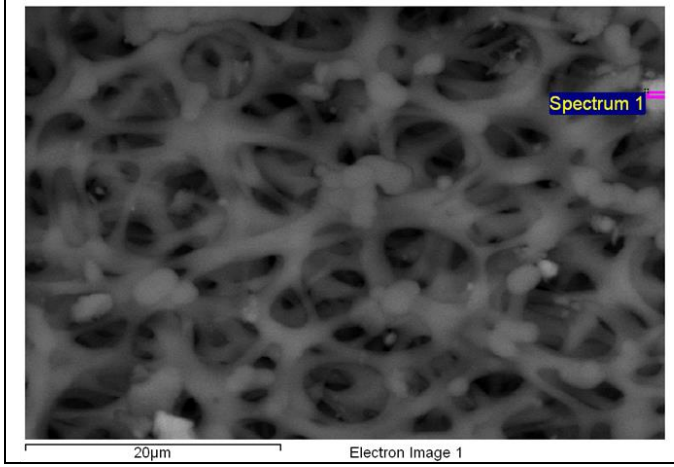


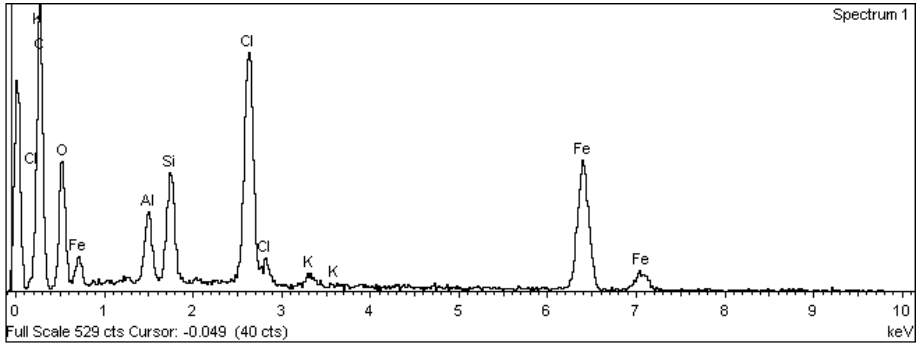
Site of interest 12



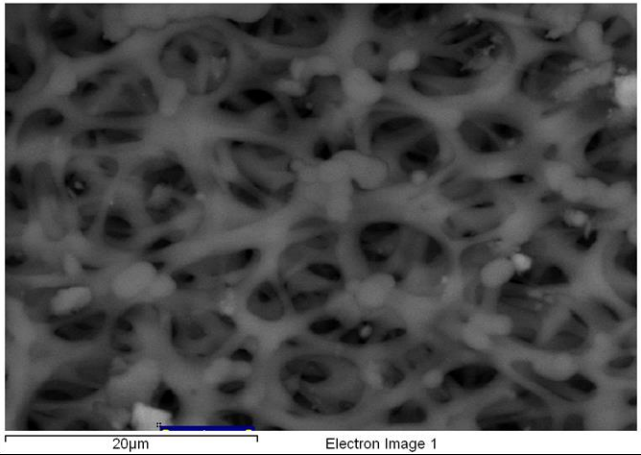


Site of interest 12

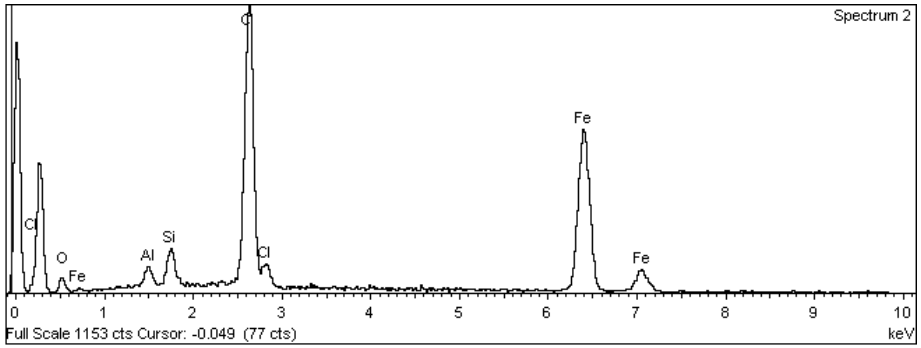




Site of interest 14



I31 EM micrograph images for F5243

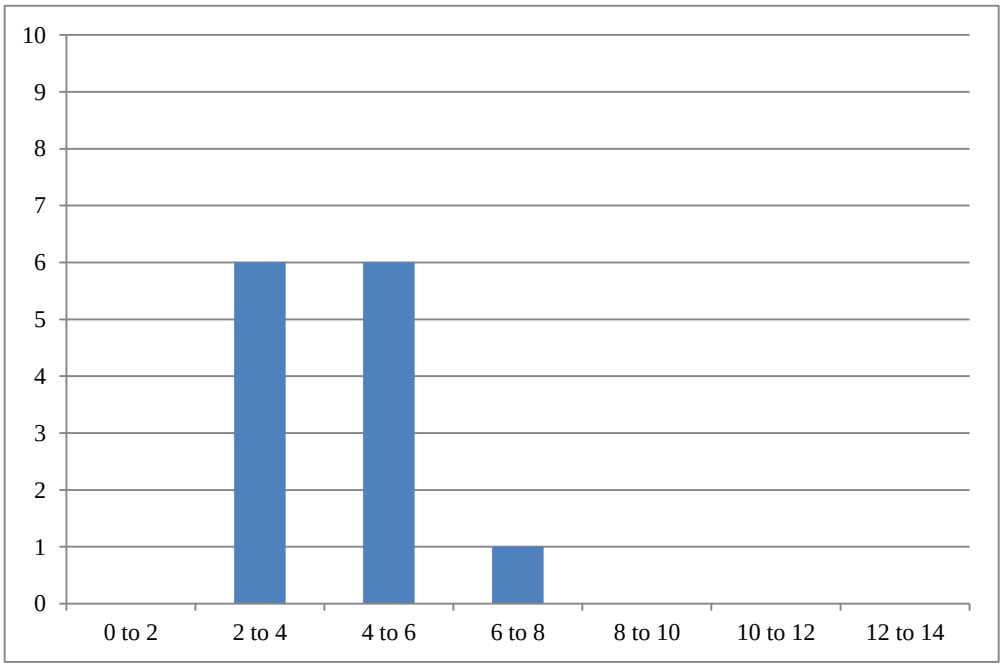


Site of interest 14

I32 Elemental spectrums for F5243

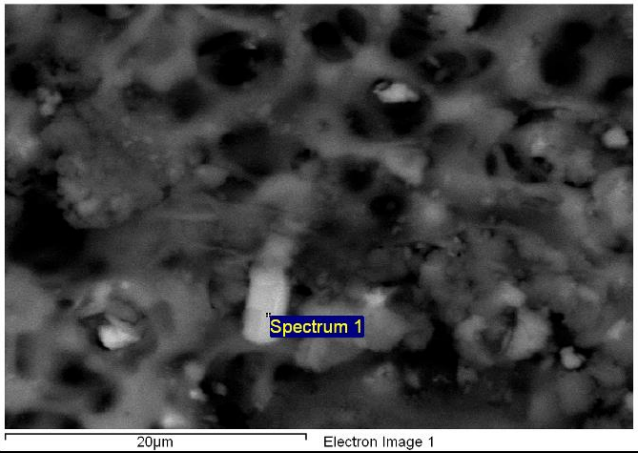
I33 Elemental scan for F6348

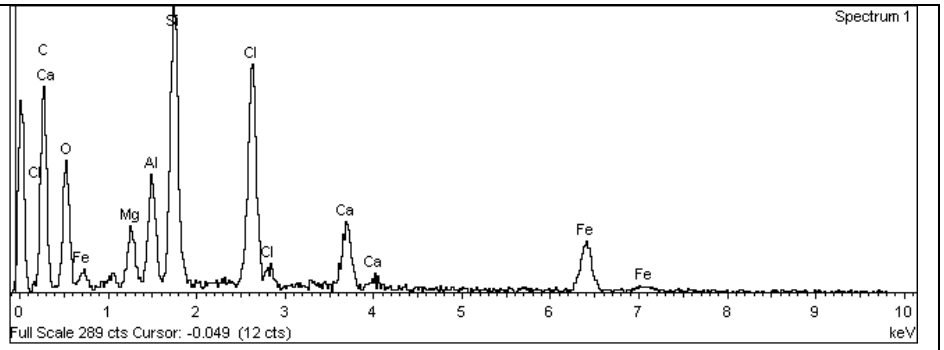
Fibre #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	1/1	5.2	O, Si	Al, Mg, Fe, Ca
2	2/1	4.0	O, Si, Al	-
3	3/1	4.2	O, Si	Al
4	3/2	5.2	O, Si	Al
5	4/1	7.2	O, Si	Fe, Mg, Al
6	5/1	4.1	O, Si	Al
7	6/2	1.4	O, Si, Al	Ca
8	7/1	1.9	O, Fe	Si
9	7/2	2.1	O, Si, Al	-
10	8/1	2.1	O, Si	Al, Ca
11	9/1	4.2	O, Si, Al	-
12	6/2	3.2	O, Si	Al, Na
13	11/1	3.9	O, Si, Al	Fe
14	12/1	4.2	O, Si	Al
15	14/1	4.0	O, Si	-



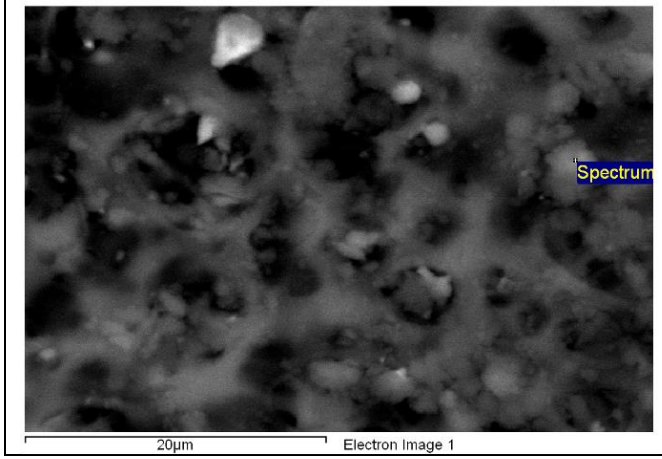
I34: Particle size distribution for F6348

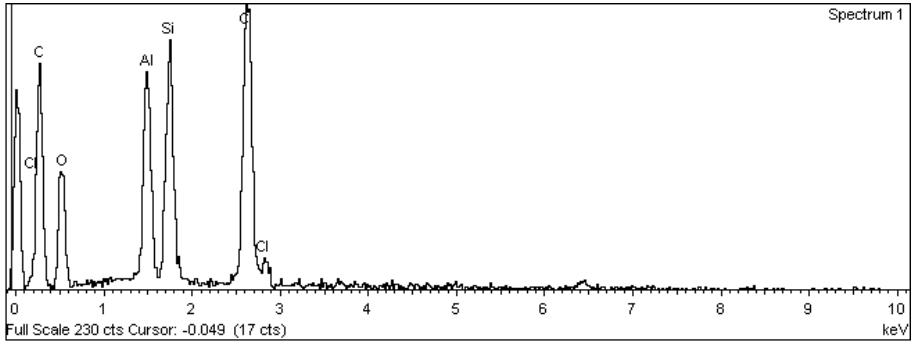
F6348



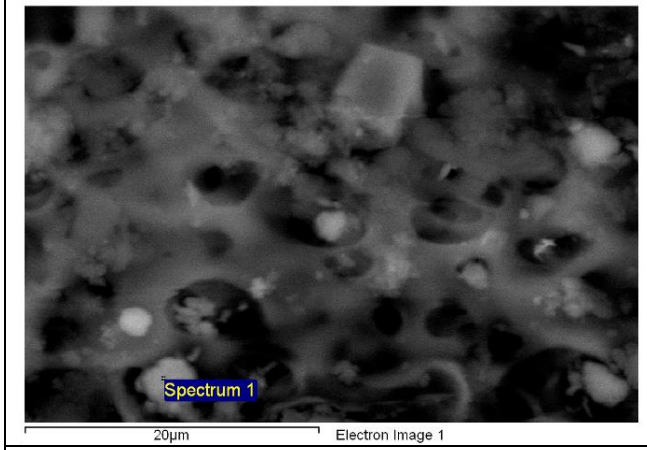


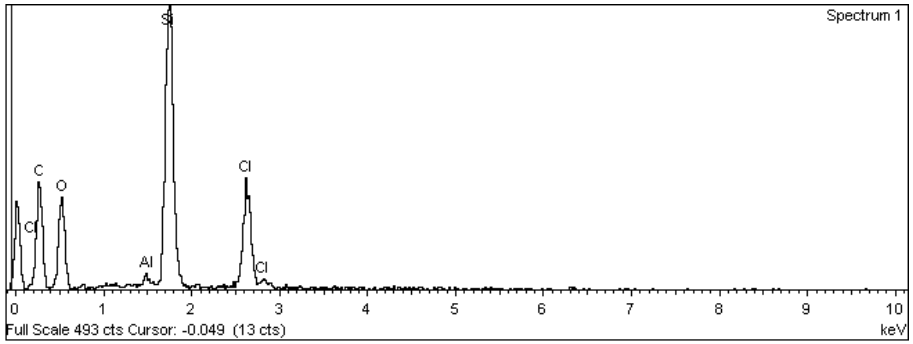
Site of interest 1



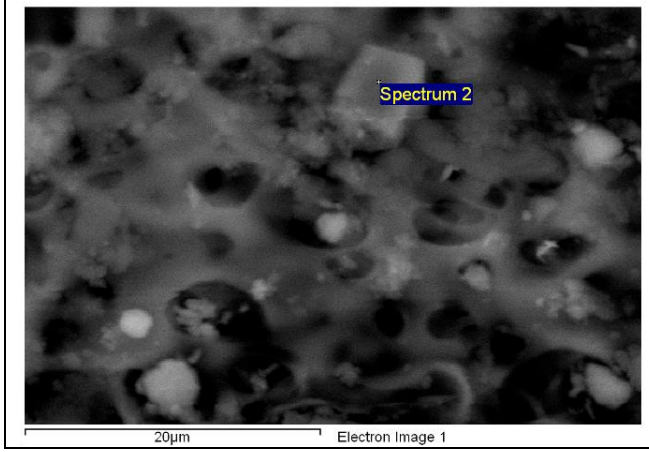


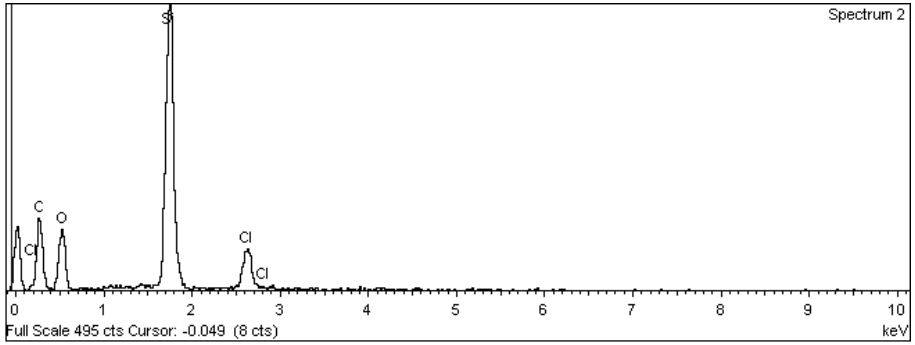
Site of interest 2



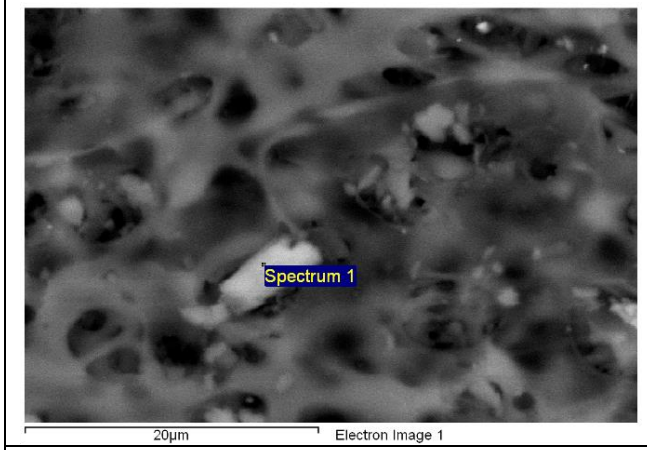


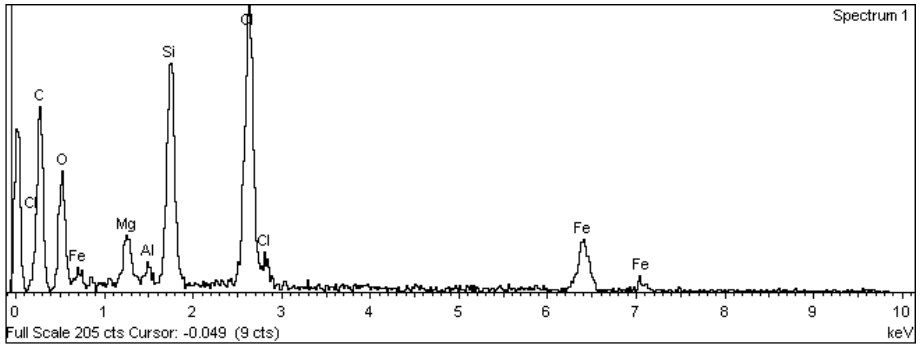
Site of interest 3



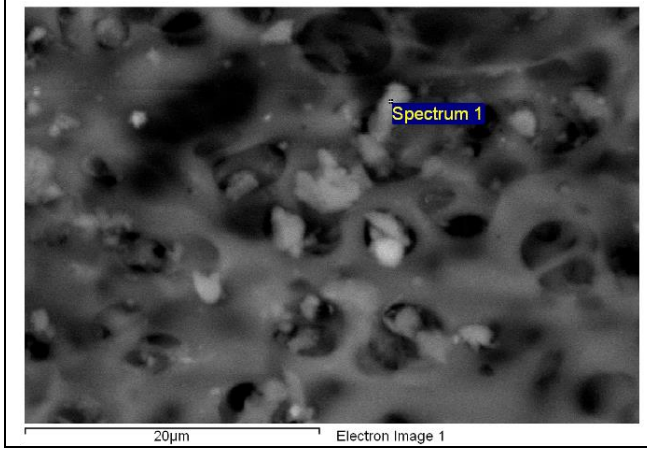


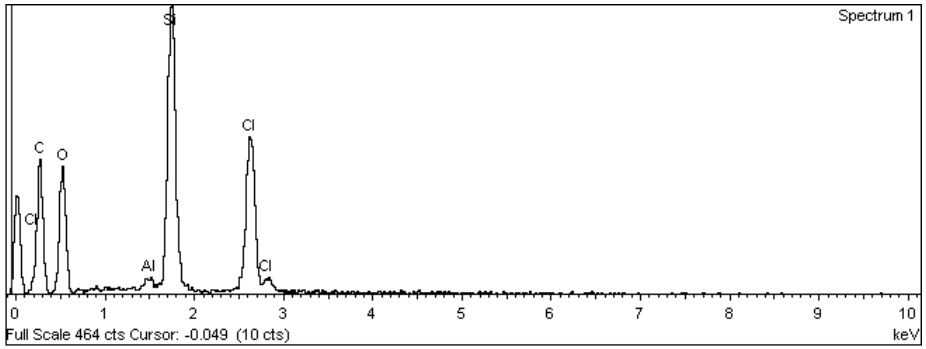
Site of interest 3



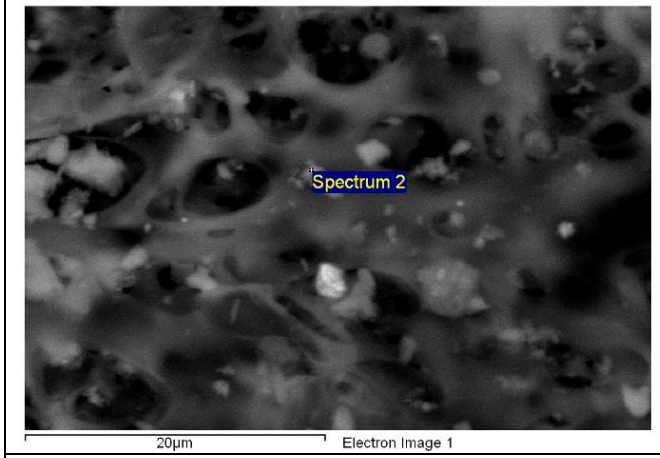


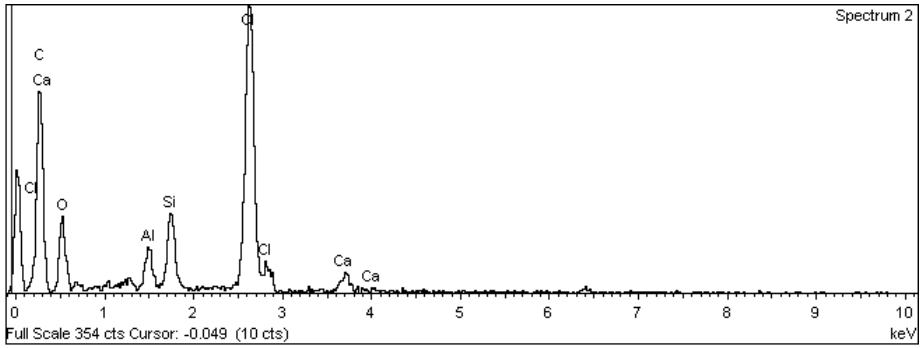
Site of interest 4



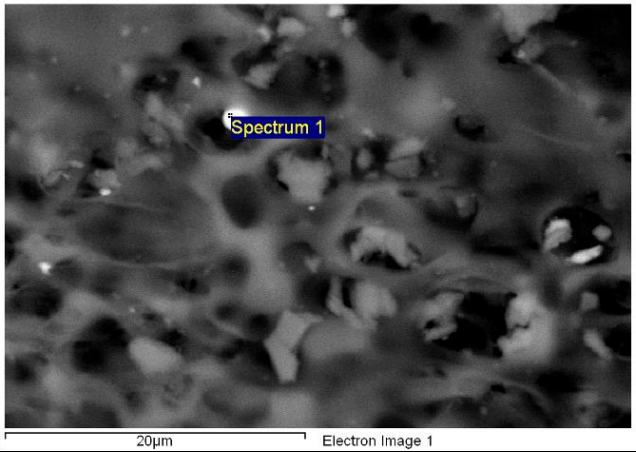


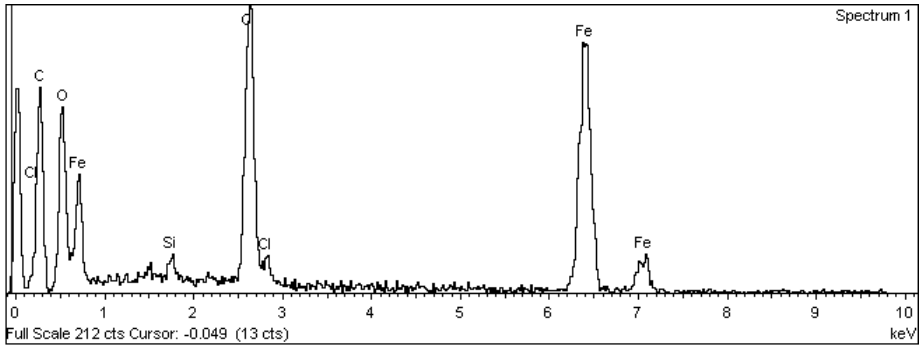
Site of interest 5



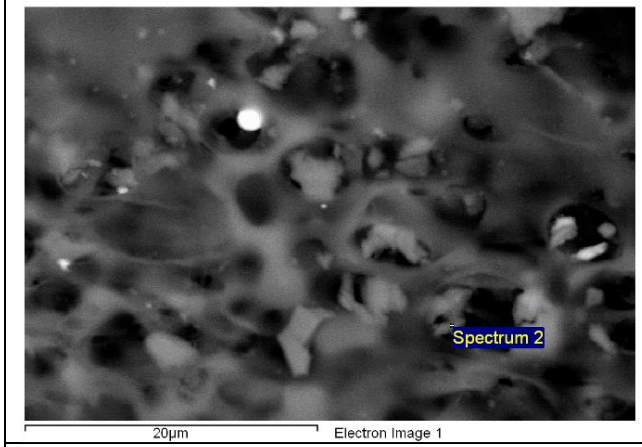


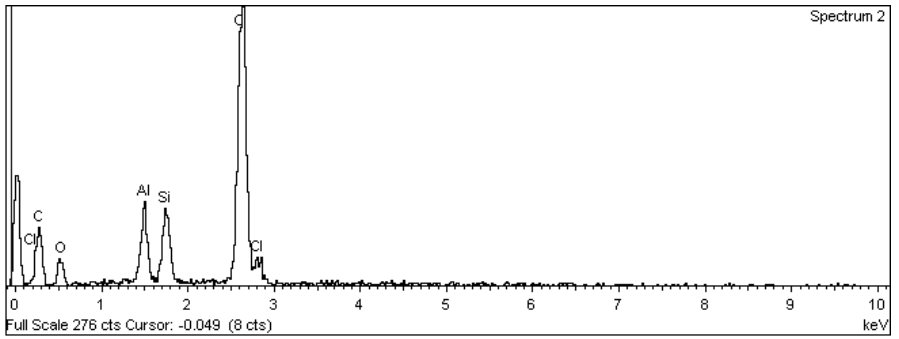
Site of interest 6



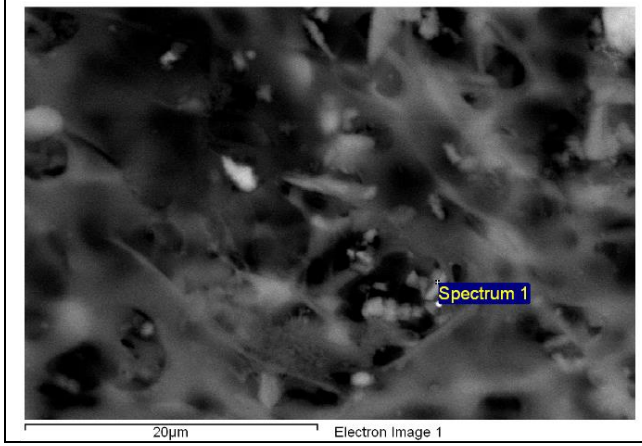


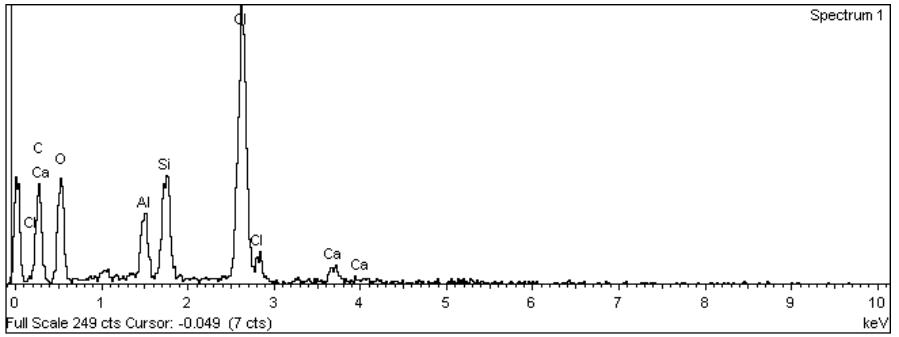
Site of interest 7



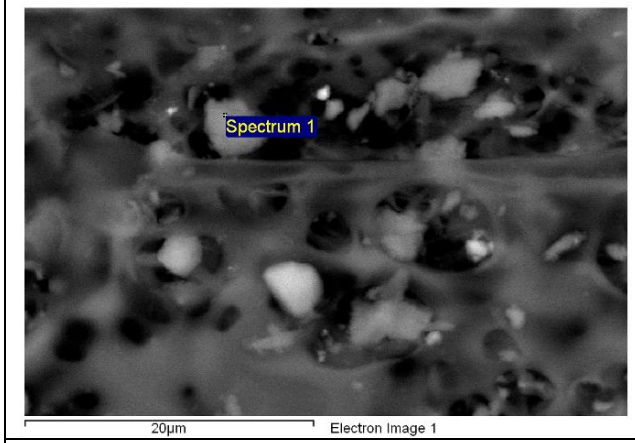


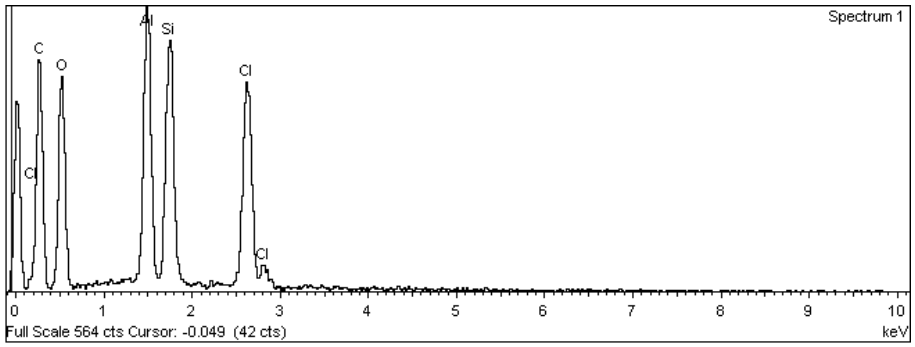
Site of interest 7



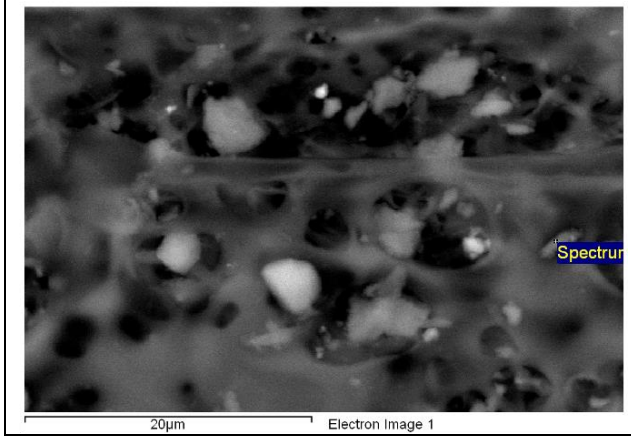


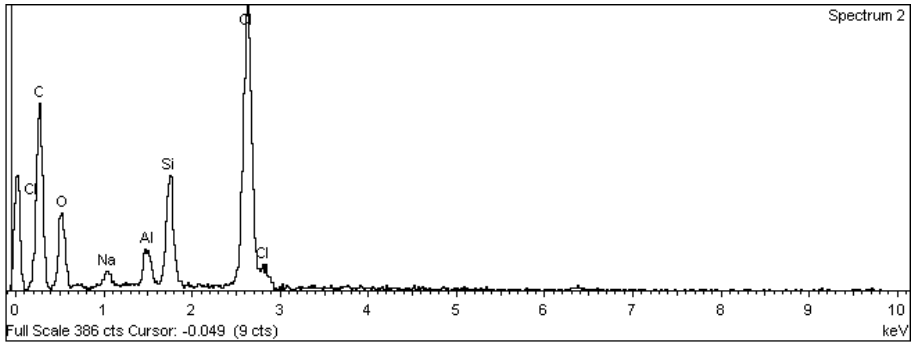
Site of interest 8



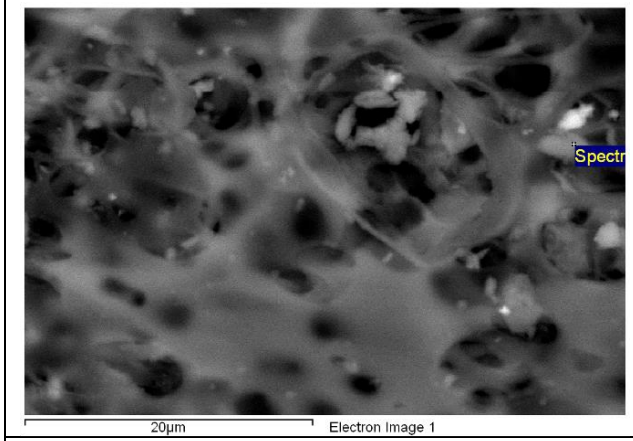


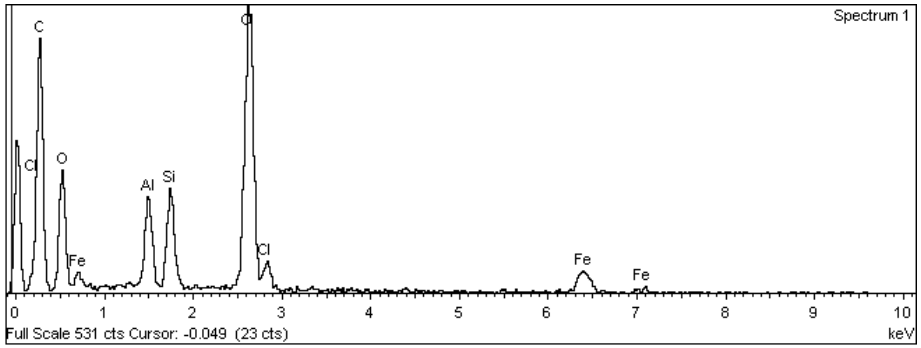
Site of interest 9



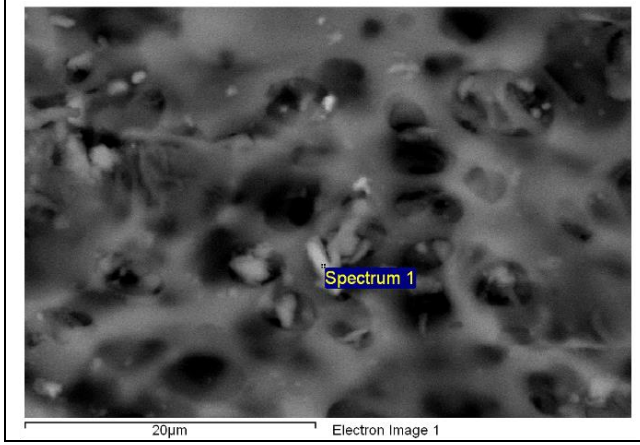


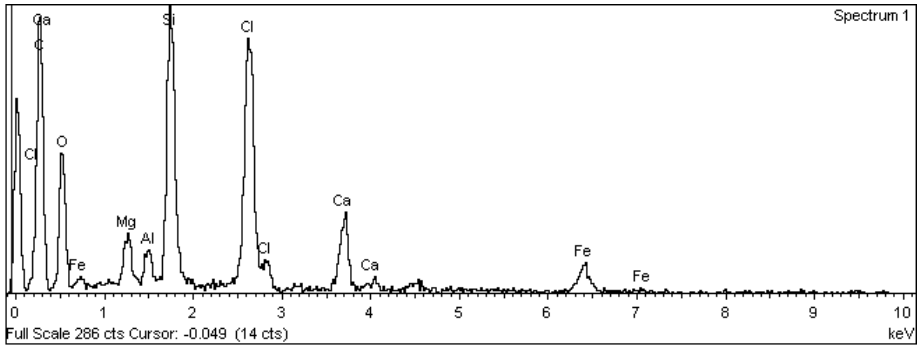
Site of interest 9



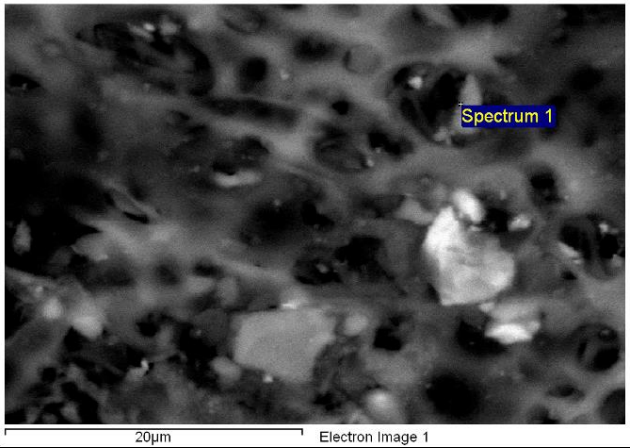


Site of interest 11

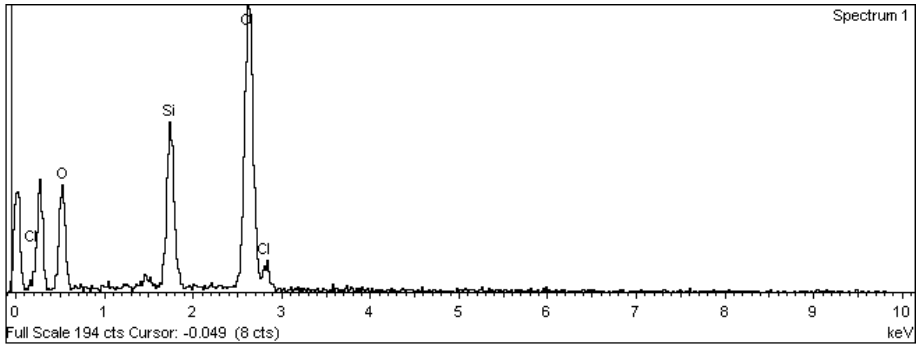




Site of interest 12



I35 EM micrograph images for F6348

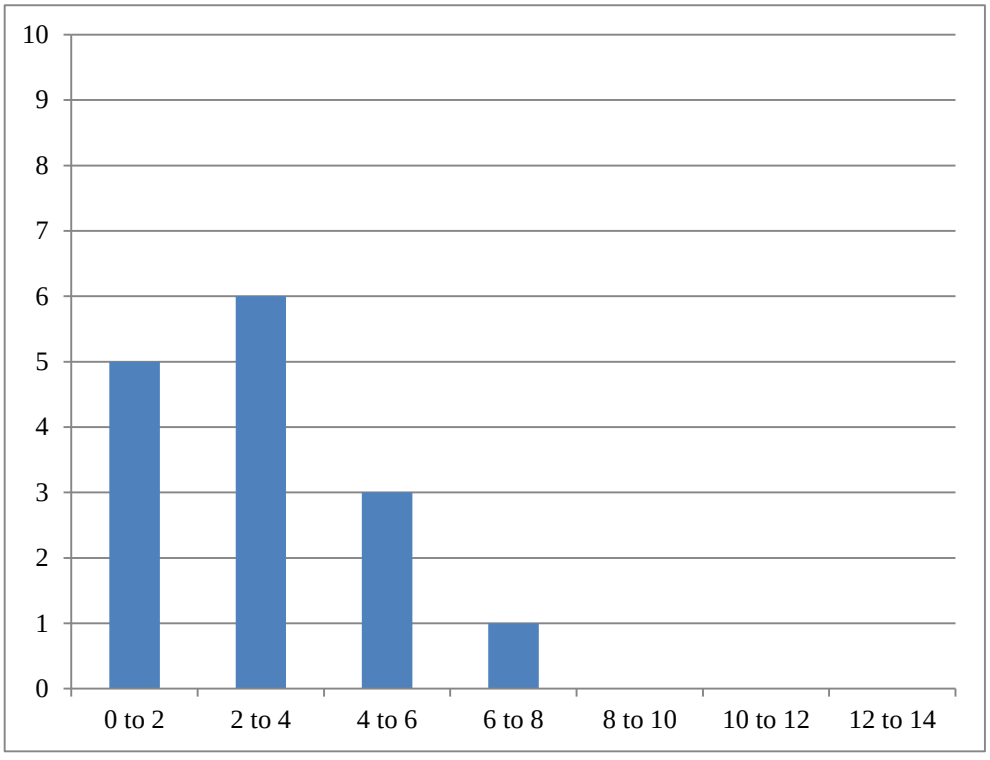


Site of interest 14

I36 Elemental spectrums for F6348

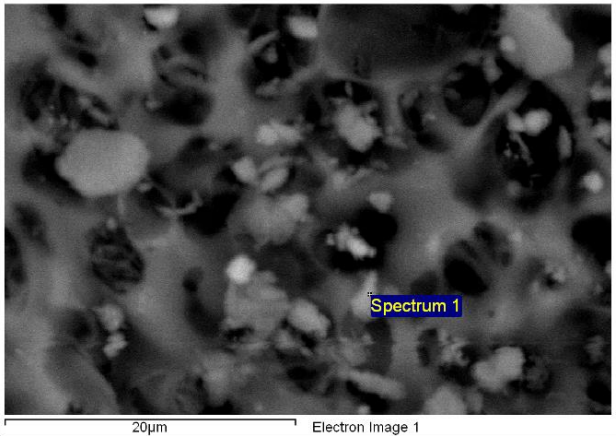
I37 Elemental scan for F5225

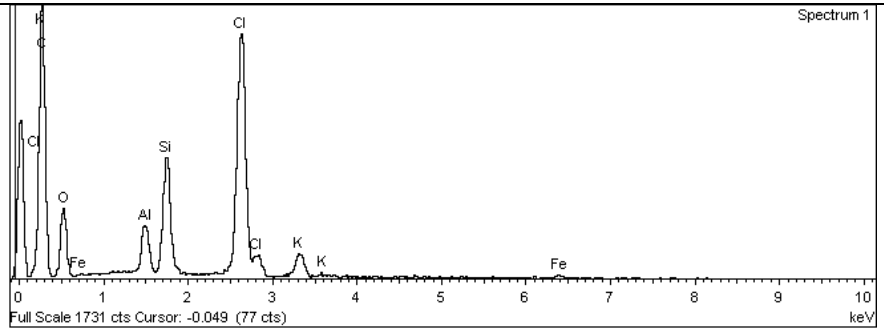
Particle #	Image/Field #	Diameter (µm)	Major Elements	Minor Elements
1	1/1	3.4	O, Si	Al, K, Fe
2	1/2	1.8	O, Si	Al, K, Fe
3	2/1	2.8	O, Si, Al	Fe
4	2/2	2.0	O, Fe	Si, Al
5	3/1	4.7	O, Ti	Si, Al
6	3/2	1.7	O, Ti	Si, Al
7	5/1	6.2	O, Si, Al	Fe
8	6/1	3.9	O, Fe	Si, Al
9	6/2	3.2	O, Si	Al
10	7/1	4.6	O, Si	Al
11	8/1	1.8	O, Fe	Si, Al
12	9/1	1.8	O, Fe	Si, Al
13	10/1	3.2	O, Si, Al	-
14	10/2	2.8	O, Si, Al	-
15	12/1	4.6	O, Si, Al	-



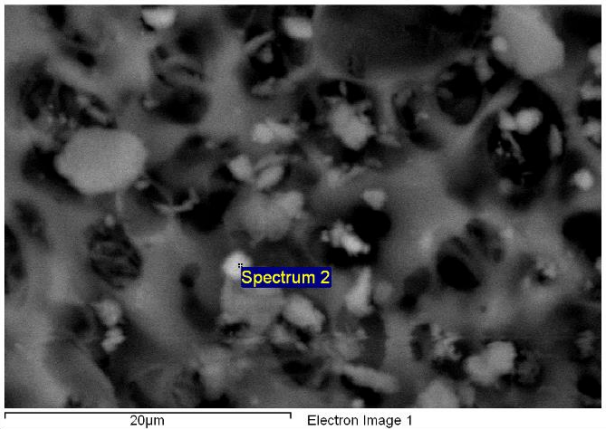
I38: Particle size distribution for F5225

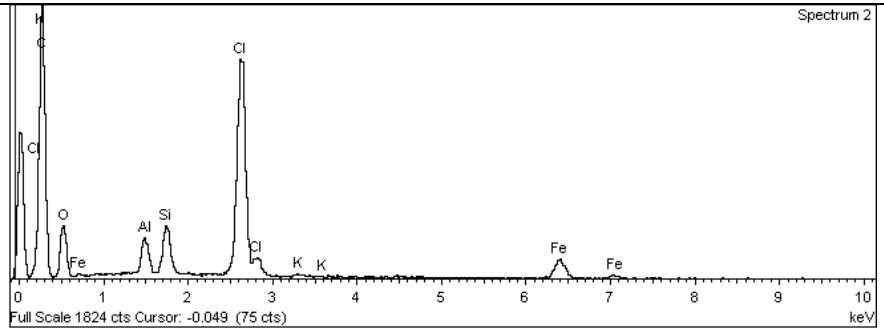
F5225



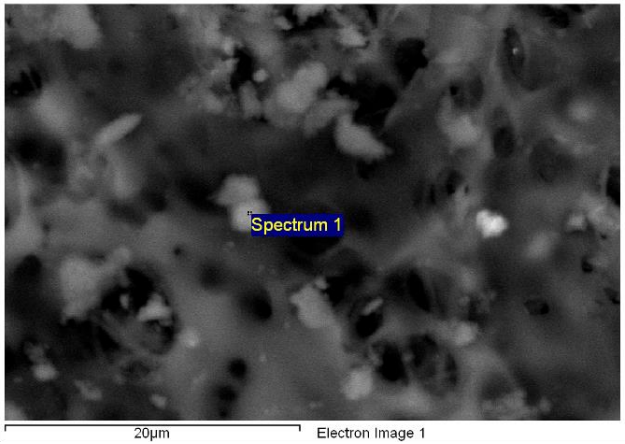


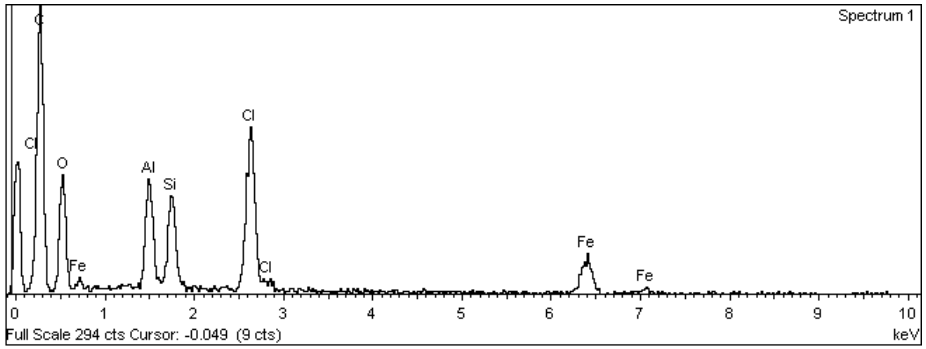
Site of interest 1



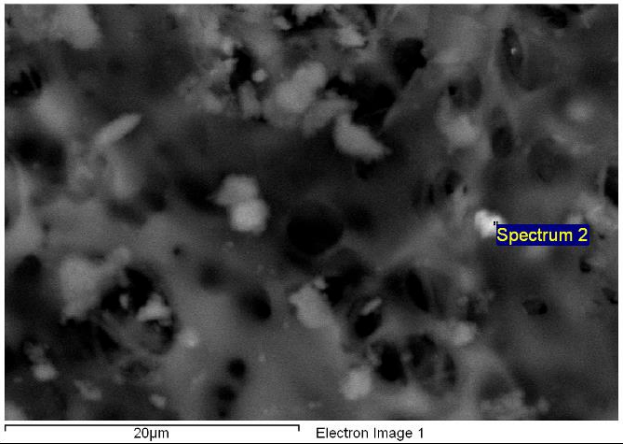


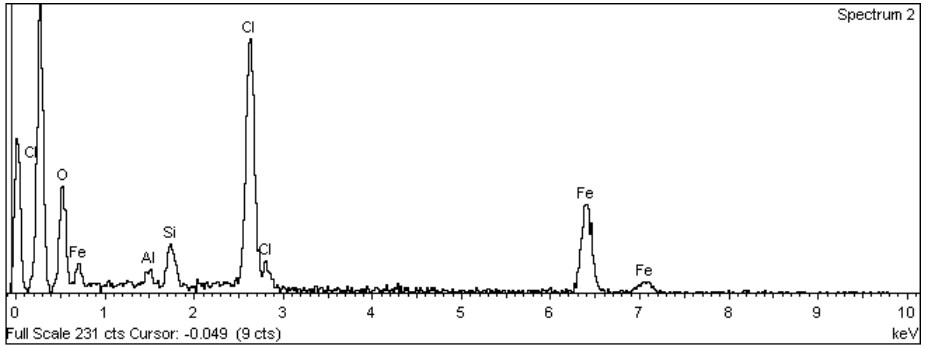
Site of interest 1



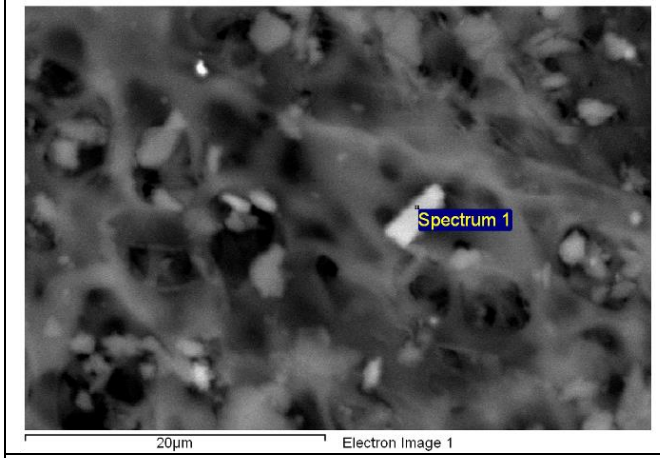


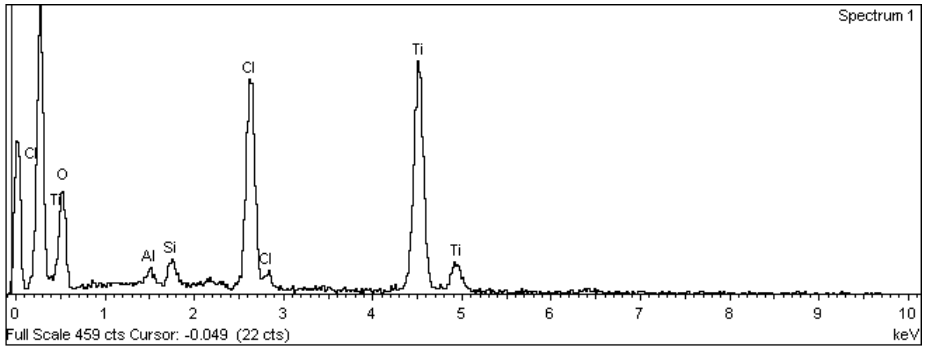
Site of interest 2



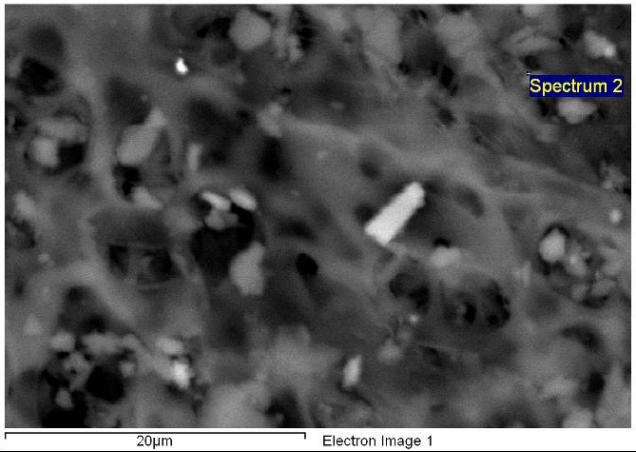


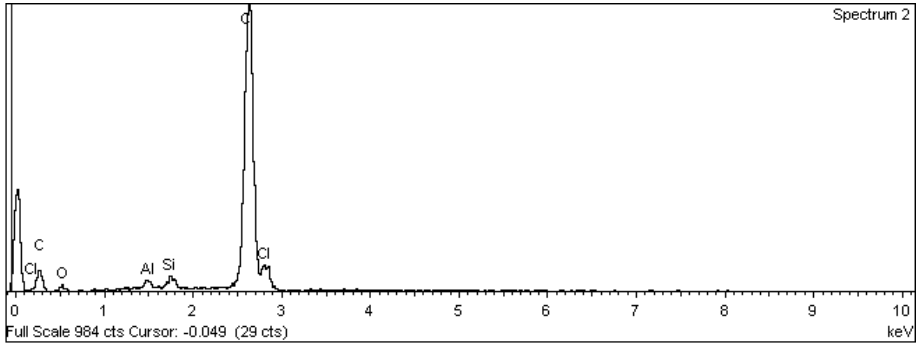
Site of interest 2



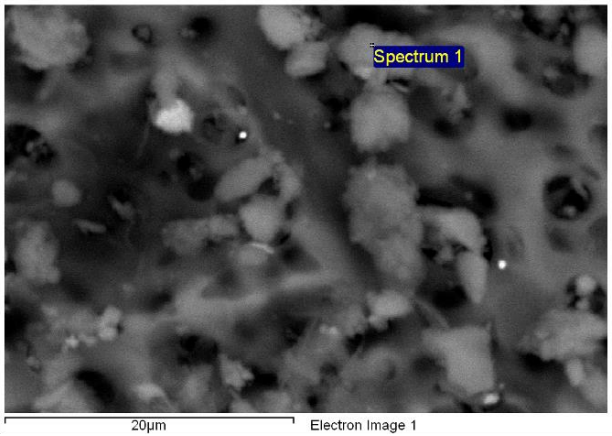


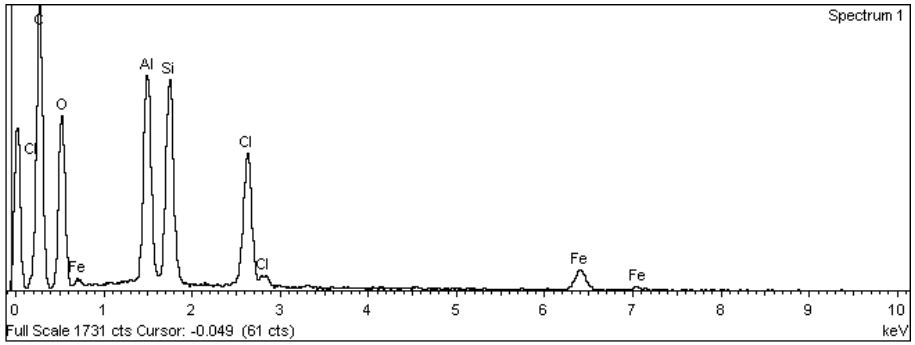
Site of interest 3



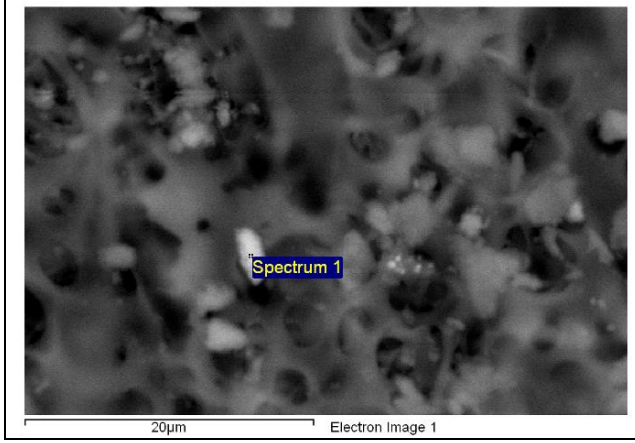


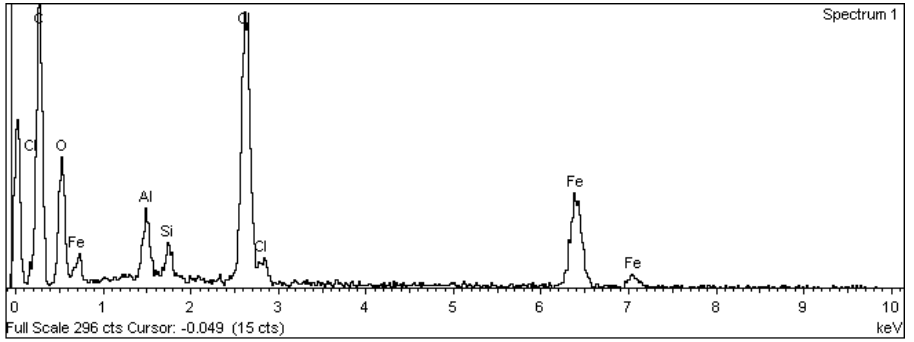
Site of interest 3



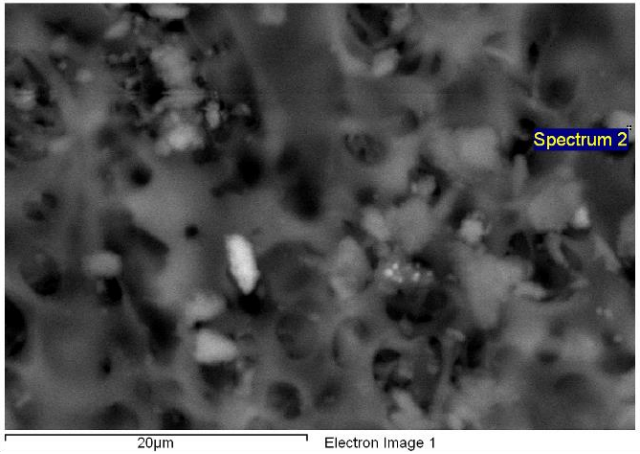


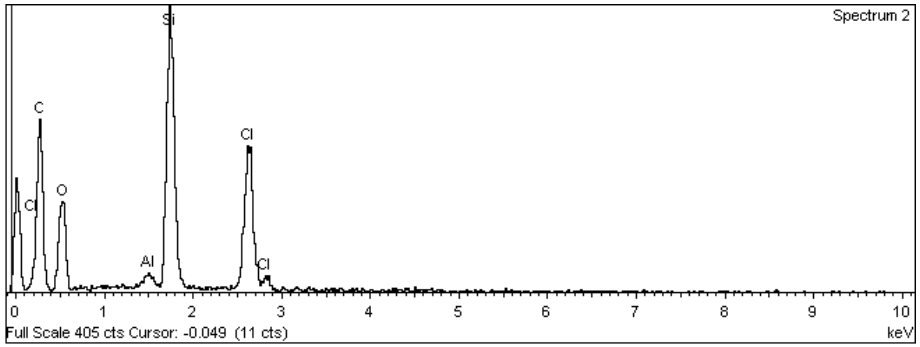
Site of interest 5



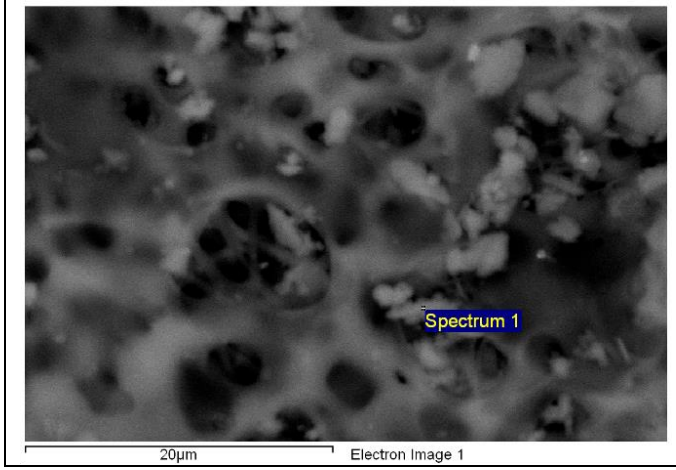


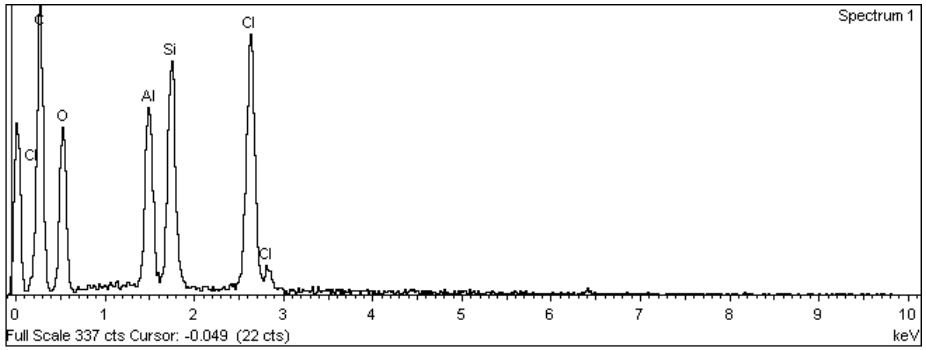
Site of interest 6



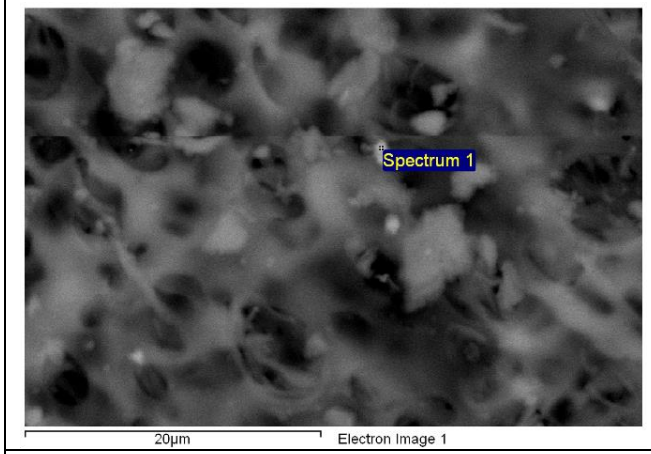


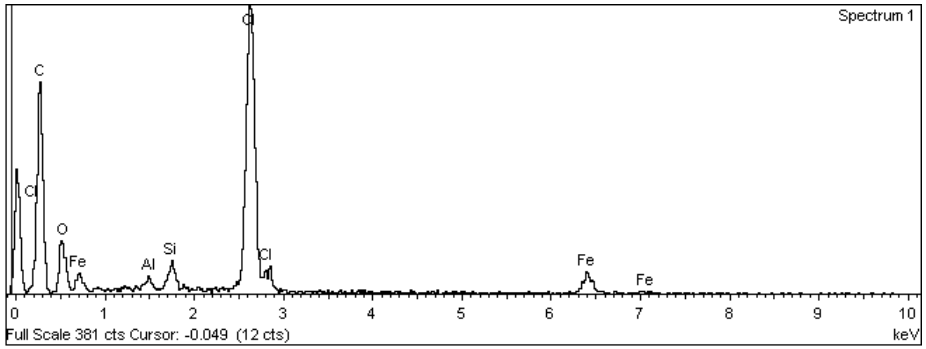
Site of interest 6



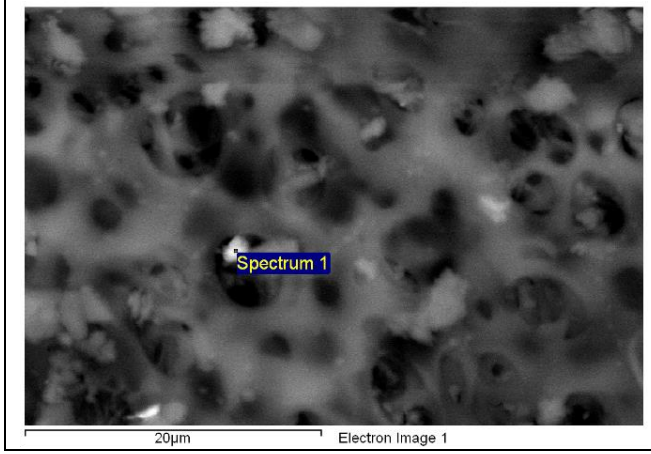


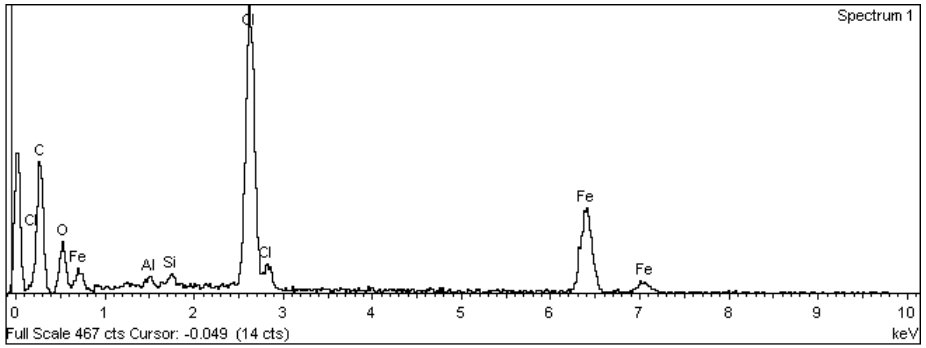
Site of interest 7



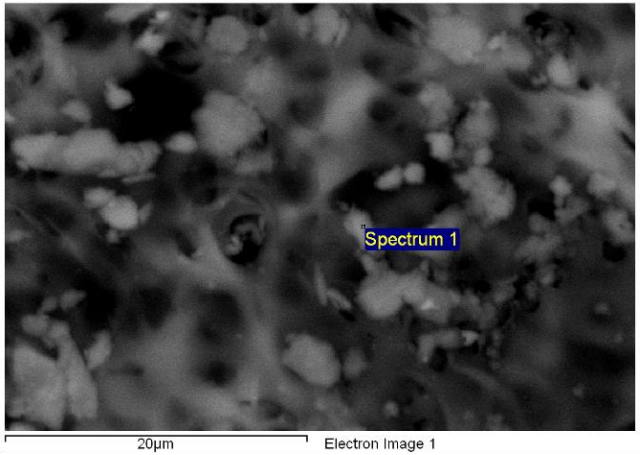


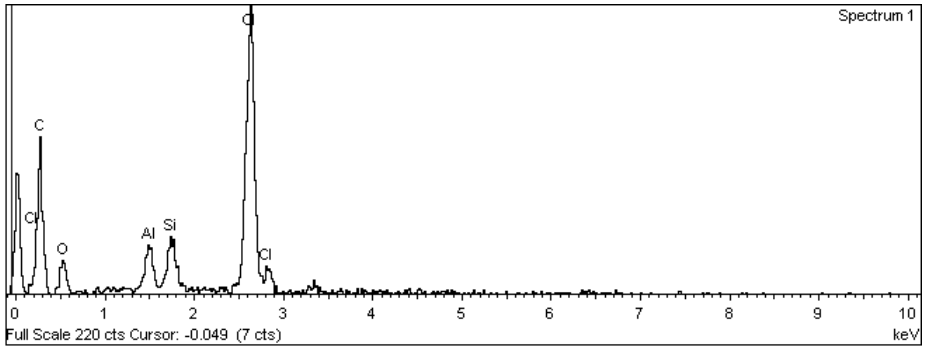
Site of interest 8



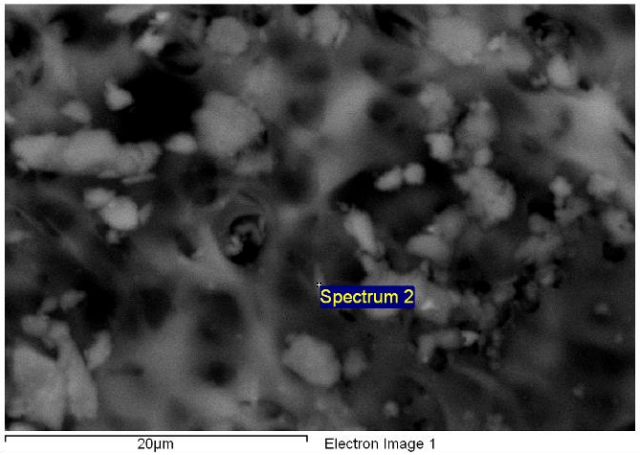


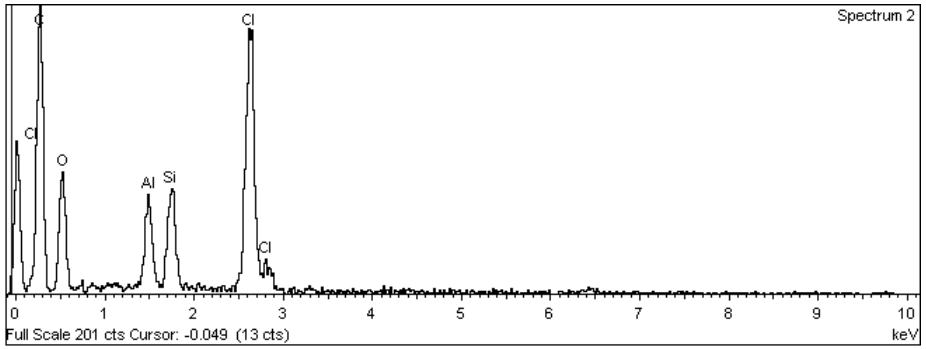
Site of interest 9



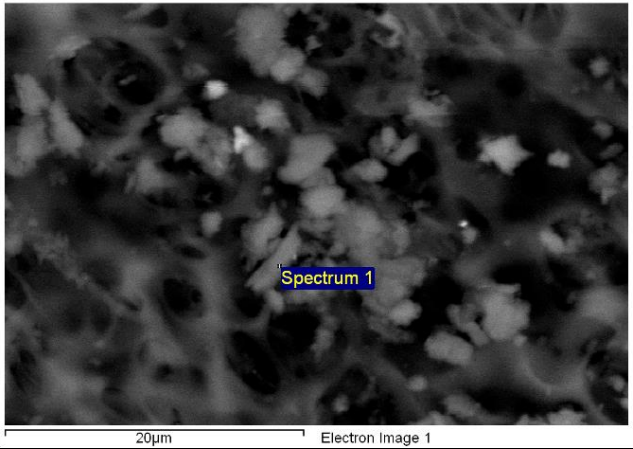


Site of interest 10

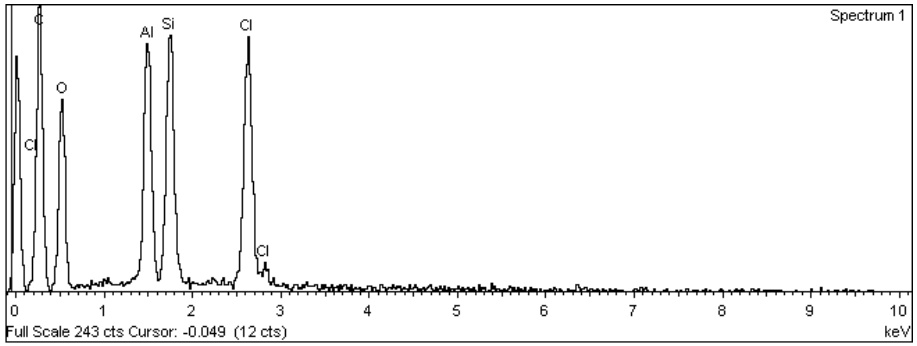




Site of interest 11



I39 EM micrograph images for F5225



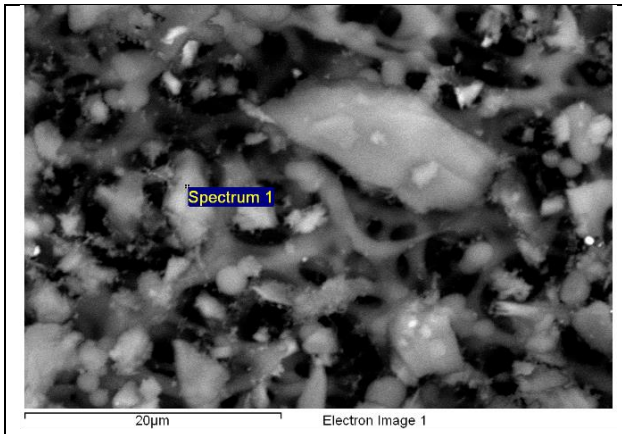
Site of interest 12

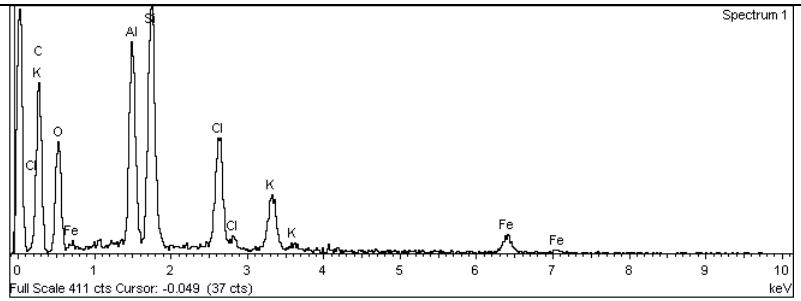
I40 Elemental spectrums for F5225

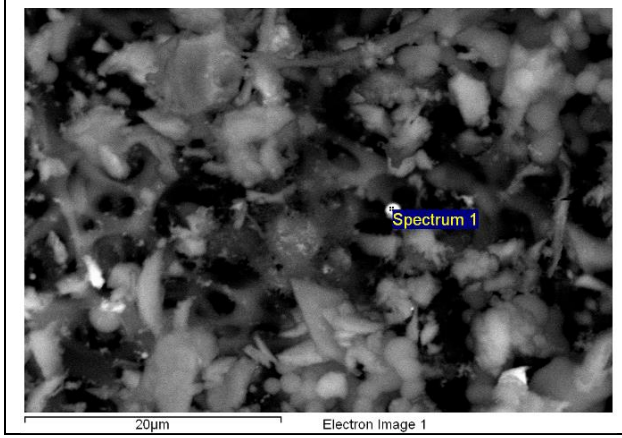
I41 Elemental scan for F5131

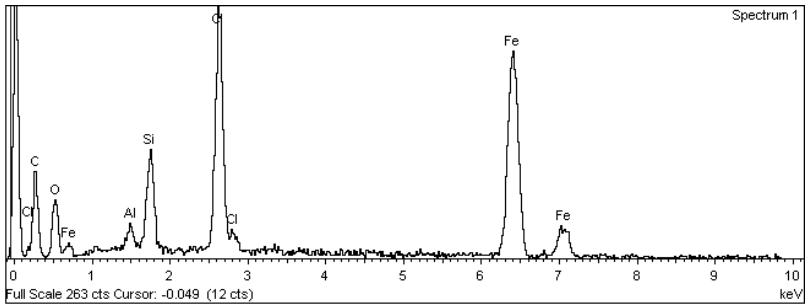
Fibre #	Image/Field #	Diameter (μm)	Major Elements	Minor Elements
1	1/1	7.5	O, Si, Al	K, Fe
2	2/1	1.0	O, Fe	Si, Al
3	2/2	2.9	O, Si	Fe, Al, K
4	3/1	2.6	O, Si	Al, K, Na
5	4/1	4.7	O, Si	Al
6	5/1	2.1	O, Si	Al
7	5/2	5.6	O, Si	Al, Ca
8	5/3	2.3	O, S, Fe	Si, Al, K
9	6/1	5.0	O, Si, Al	K, Fe
10	7/1	7.5	O, Si, Fe	Al
11	8/1	5.1	O, Si	Al, K, Fe
12	9/1	3.3	O, Si	Al, K, Fe, Na, Mn
13	10/1	2.4	O, Si	F, Fe, Al, K
14	12/1	2.9	O, S, Fe	Si, Al
15	13/1	22.5	O, Si	Al

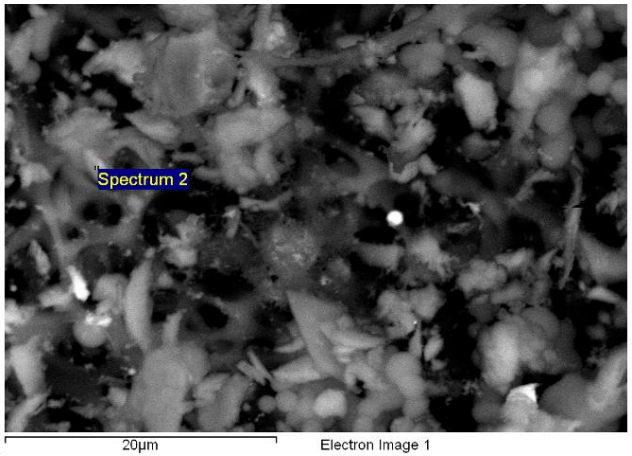
F5131

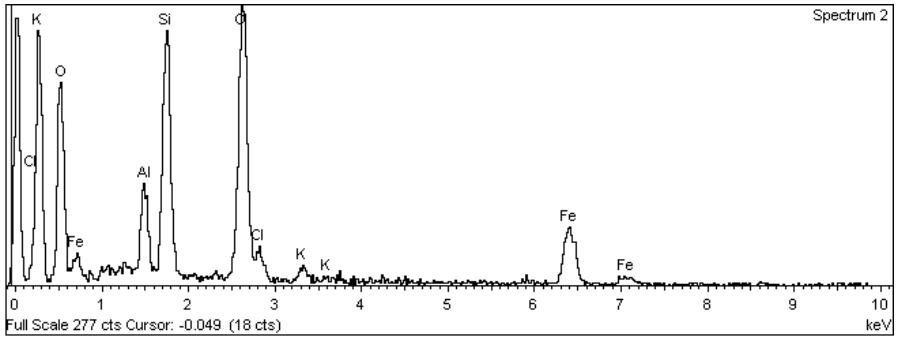

Spectrum 1
20µm
Electron Image 1

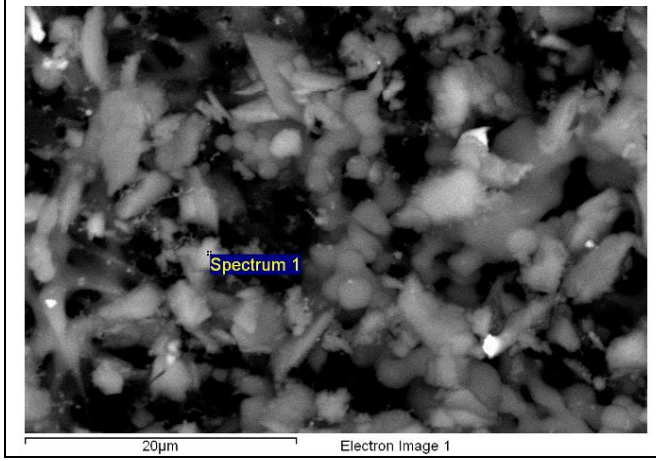

Spectrum 1
C
K
O
Cl
Fe
Al
Si
Cl
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 411 cts Cursor: -0.049 (37 cts)
keV

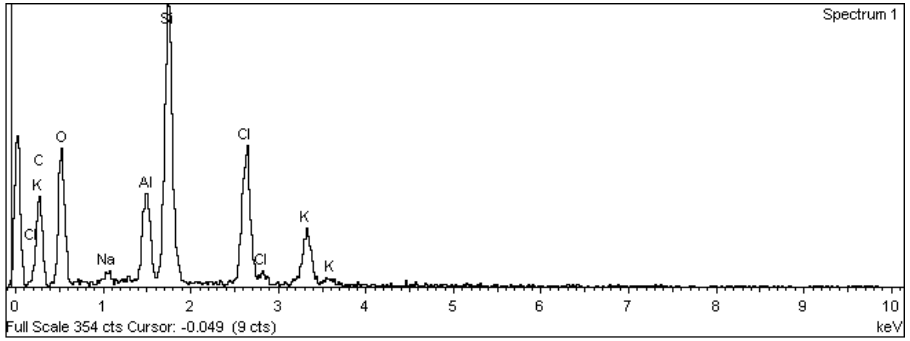

Spectrum 1
20µm
Electron Image 1

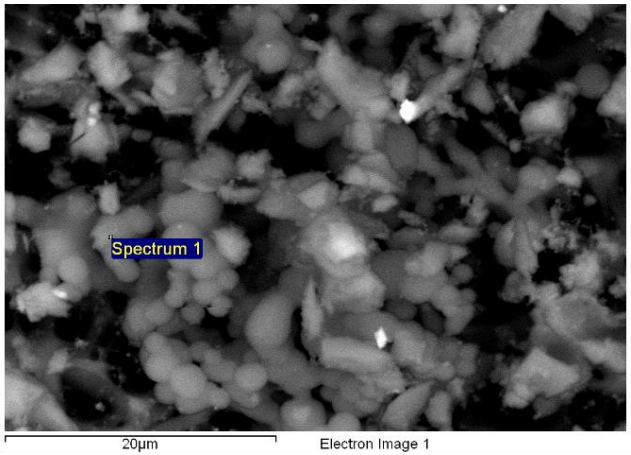

Spectrum 1
Cl
Fe
Si
C
O
Cl
Fe
Al
Cl
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 263 cts Cursor: -0.049 (12 cts)
keV

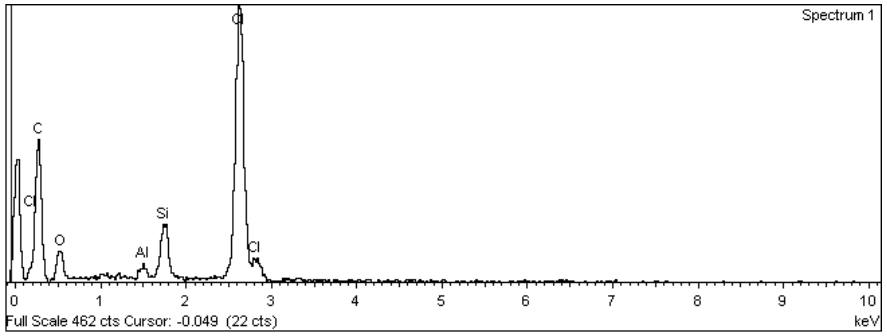

Spectrum 2
20µm
Electron Image 1

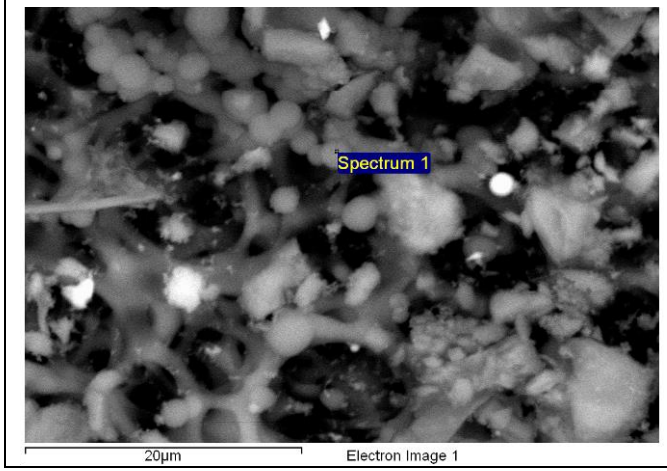

Spectrum 2
K
Si
Cl
O
Al
Fe
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 277 cts Cursor: -0.049 (18 cts)
keV

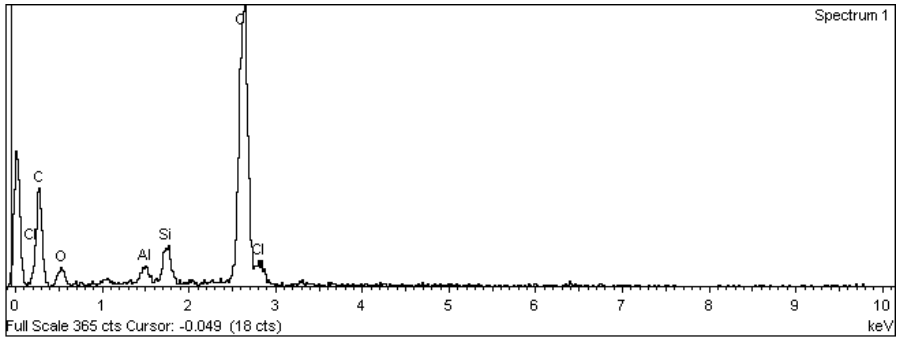

Spectrum 1
20µm
Electron Image 1

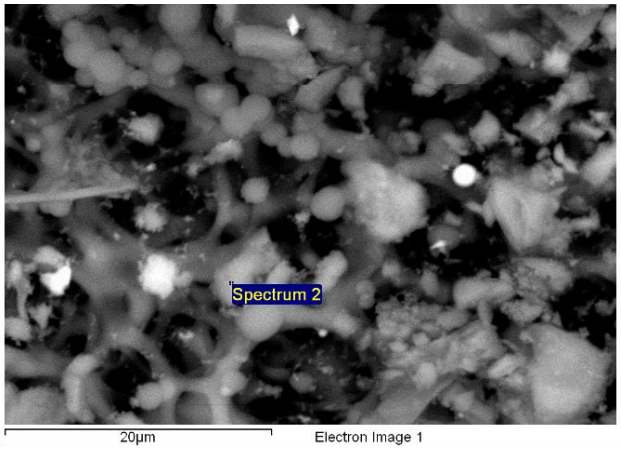

Spectrum 1
Si
O
C
K
Cl
Na
Al
Cl
K
Cl
K
0 1 2 3 4 5 6 7 8 9 10
Full Scale 354 cts Cursor: -0.049 (9 cts)
keV

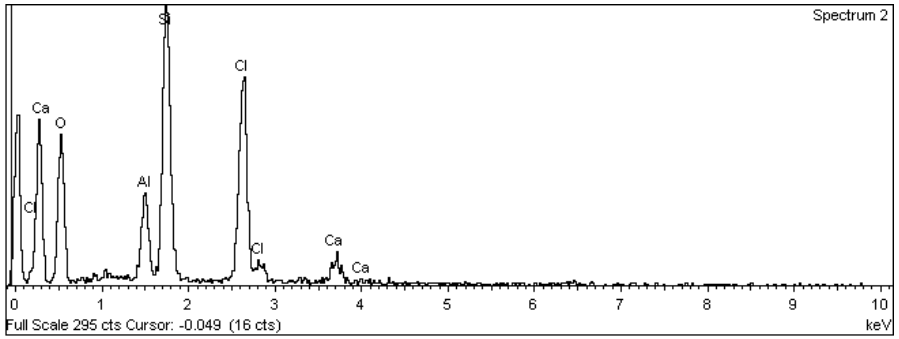

Spectrum 1
20µm
Electron Image 1

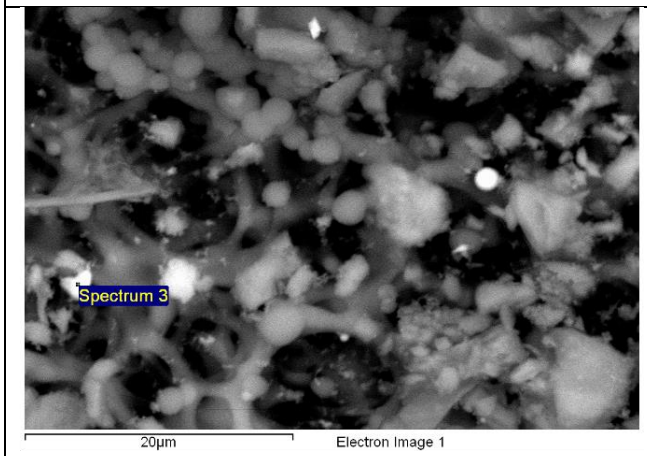

Spectrum 1
C
Cl
O
Al
Si
Cl
Cl
0 1 2 3 4 5 6 7 8 9 10
Full Scale 462 cts Cursor: -0.049 (22 cts)
keV

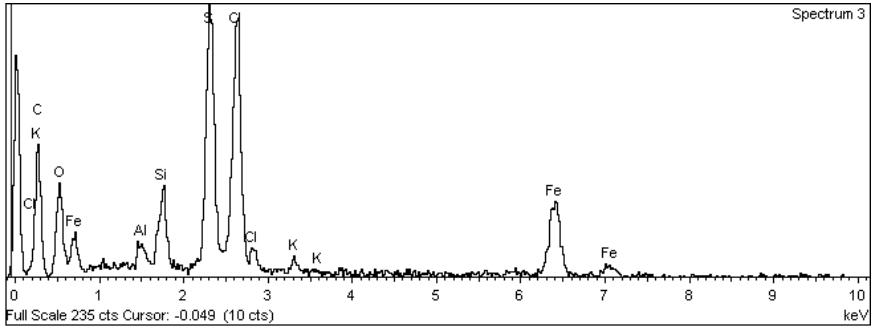

Spectrum 1
20µm
Electron Image 1

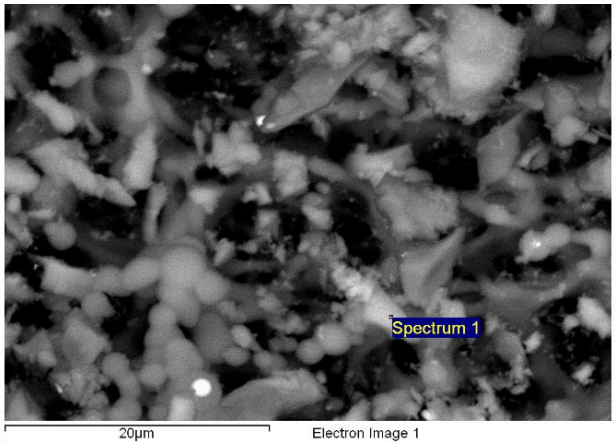

Spectrum 1
Cl
C
Cl
O
Al
Si
Cl
0 1 2 3 4 5 6 7 8 9 10
Full Scale 365 cts Cursor: -0.049 (18 cts)
keV

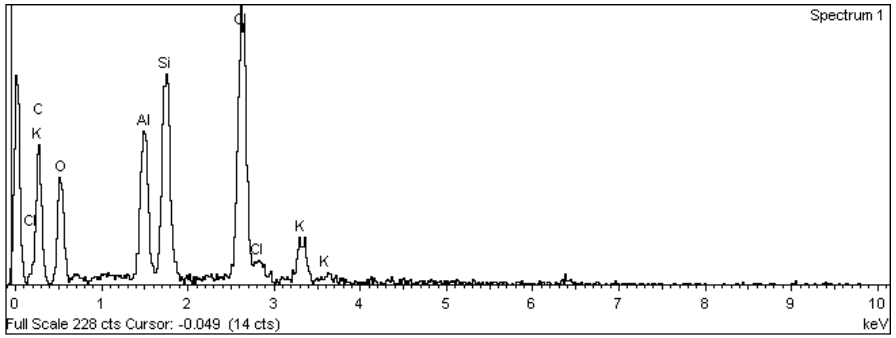

Spectrum 2
20µm
Electron Image 1

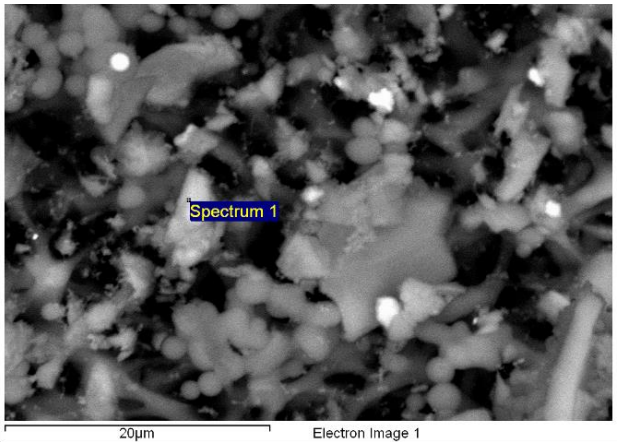

Spectrum 2
Si
Cl
Ca
O
Al
Cl
Ca
Ca
0 1 2 3 4 5 6 7 8 9 10
Full Scale 295 cts Cursor: -0.049 (16 cts)
keV

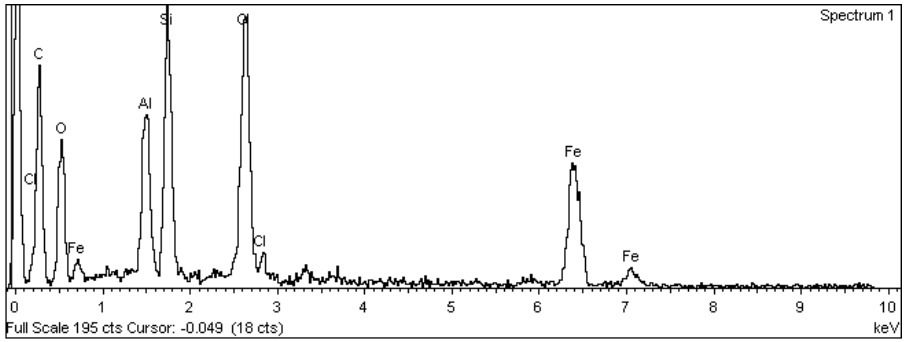

Spectrum 3
20µm
Electron Image 1

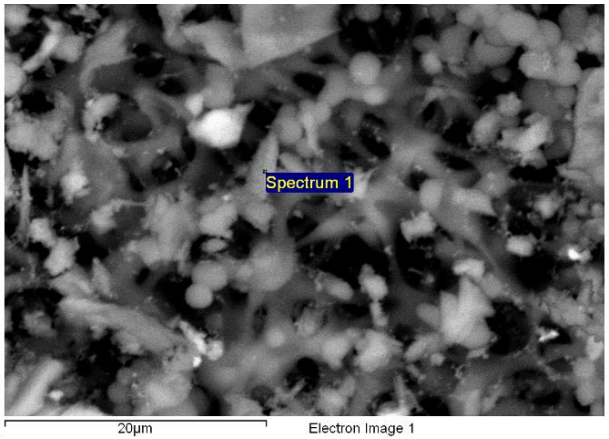

Spectrum 3
Si
Cl
C
K
O
Cl
Fe
Al
Si
Cl
K
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 235 cts Cursor: -0.049 (10 cts)
keV

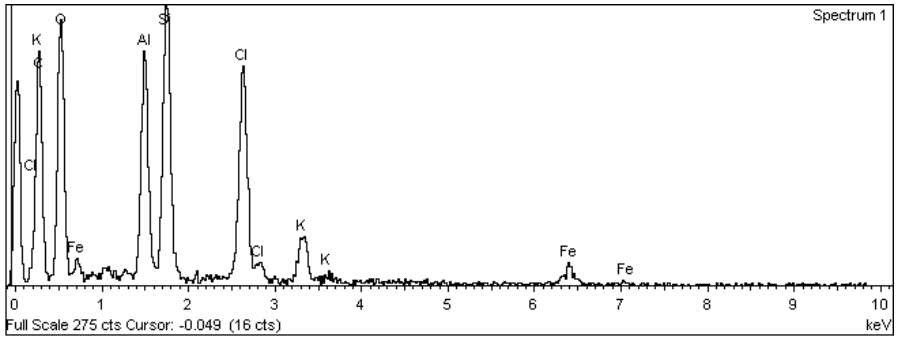

Spectrum 1
20µm
Electron Image 1

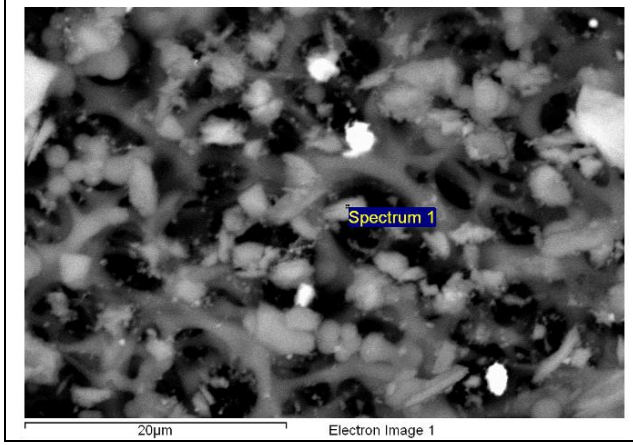

Spectrum 1
C
K
O
Al
Si
Cl
K
K
Cl
0 1 2 3 4 5 6 7 8 9 10
Full Scale 228 cts Cursor: -0.049 (14 cts)
keV

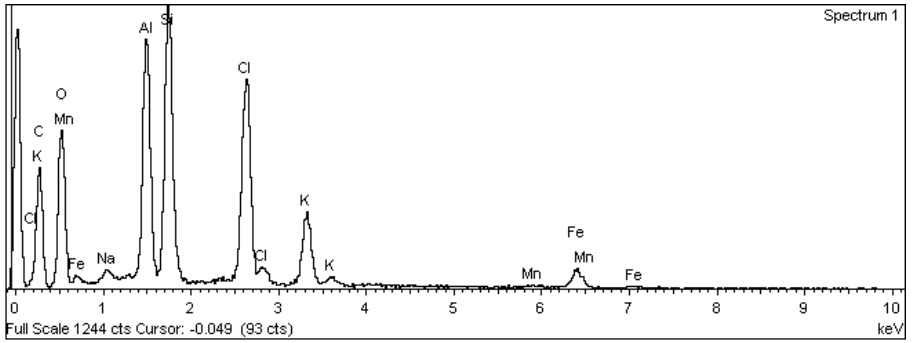

Spectrum 1
20µm
Electron Image 1

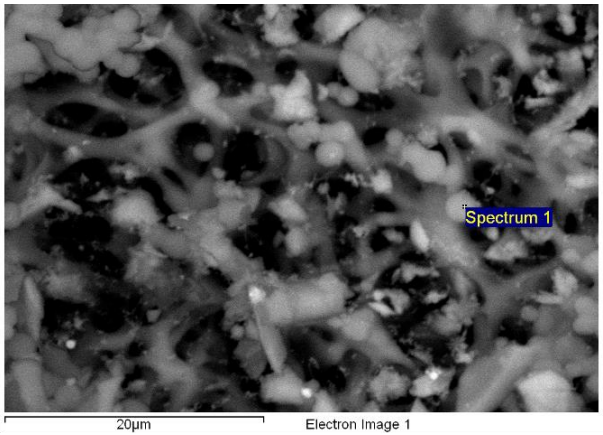

Spectrum 1
C
O
Al
Si
Cl
Cl
Fe
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 195 cts Cursor: -0.049 (18 cts)
keV

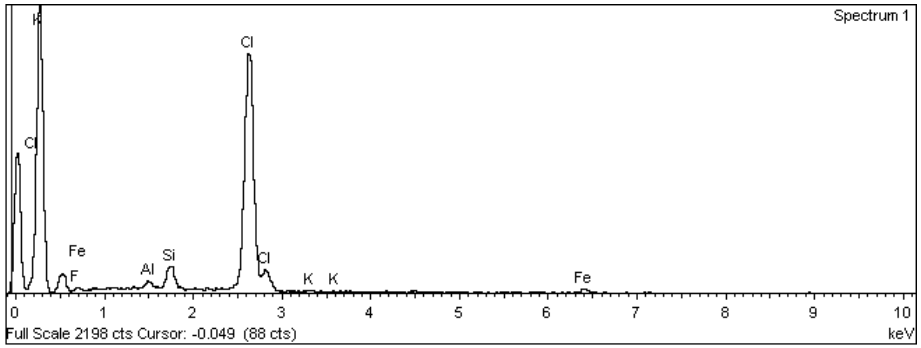

Spectrum 1
20µm
Electron Image 1

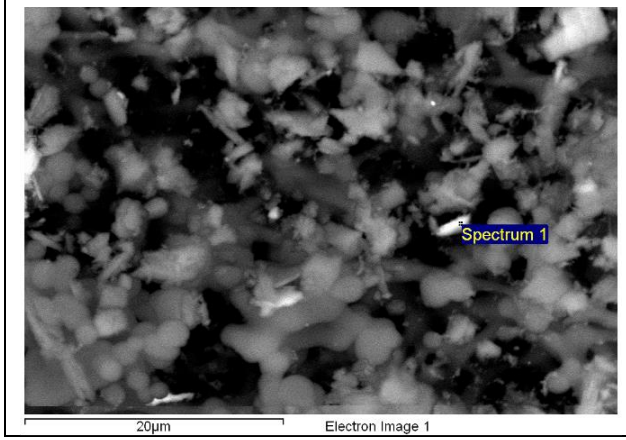

Spectrum 1
O
K
Al
Si
Cl
Fe
K
Cl
K
Fe
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 275 cts Cursor: -0.049 (16 cts)
keV

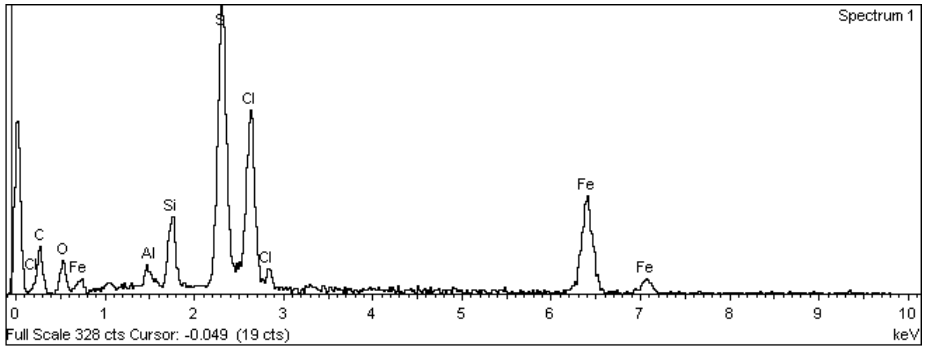

Spectrum 1
20µm
Electron Image 1

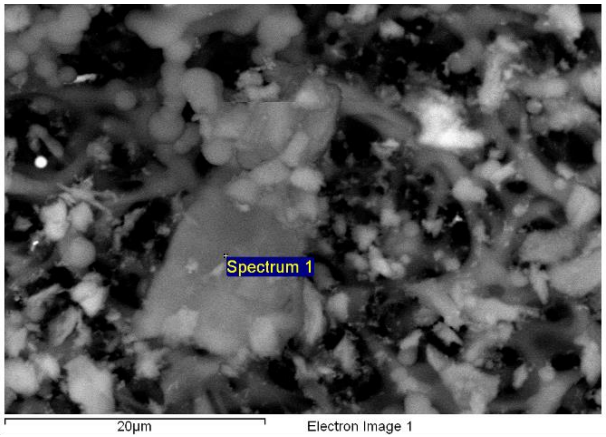

Spectrum 1
Al
Si
Cl
O
Mn
C
K
Cl
Fe
Na
Cl
K
K
Fe
Mn
Mn
Fe
0 1 2 3 4 5 6 7 8 9 10
Full Scale 1244 cts Cursor: -0.049 (93 cts)
keV


Spectrum 1
20µm
Electron Image 1

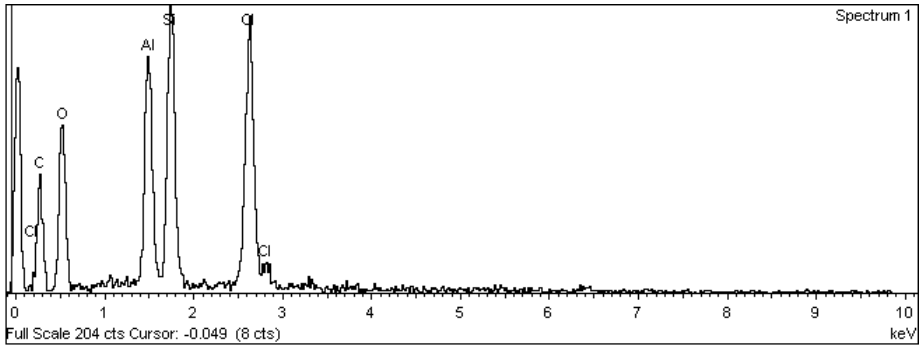

Spectrum 1
Cl
Cl
Fe
F
Al
Si
Cl
K
K
Fe
0
1
2
3
4
5
6
7
8
9
10
Full Scale 2198 cts Cursor: -0.049 (88 cts)
keV


Spectrum 1
20µm
Electron Image 1


Spectrum 1
Si
Cl
Fe
C
O
Cl
Fe
Al
Si
Cl
Fe
0
1
2
3
4
5
6
7
8
9
10
Full Scale 328 cts Cursor: -0.049 (19 cts)
keV



I42 EM micrograph images for F5131



I43 Elemental spectrums for F5131