MONITORING AND STATISTICAL MODELLING OF DUST CONCENTRATION OF SOME TURKISH LIGNITES UNDER LABORATORY CONDITIONS

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MONITORING AND STATISTICAL MODELLING OF DUST CONCENTRATION OF SOME TURKISH LIGNITES UNDER LABORATORY CONDITIONS

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ABSTRACT

MONITORING AND STATISTICAL MODELLING OF DUST CONCENTRATION OF SOME TURKISH LIGNITES UNDER LABORATORY CONDITIONS

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Although technological developments enable maximum safety, high dust formation is still a crucial problem in coal mining sector. This study is aimed to investigate the relationship between amount of coal dust produced during cutting operation and some important coal properties together with cutting parameters for different particle size ranges in laboratory conditions. For this purpose, six Turkish lignite samples were used in the experiments.

Two experiment sets were designed to generate coal dust by using cutting action of the saw. First group of experiments were conducted in large scale saw system by using saws having three different diameters and dust concentration measurements were done for three group of particle size namely: 0-2.5 µm, 0-5 µm and 0-10 µm.

Second group of experiments were done in small scale saw system by changing the table advancing speed and tip speed of the system. For this group of experiments,

only one type of lignite samples were used. These measurements were carried out only 0-10 µm particle size range by using a saw with 30 cm in diamater.

In this study, to characterize the lignite samples; proximate, petrographic and grindability analysis (HGI) were made. During the experiments, dust concentrations were measured by using Microdust Pro real time dust monitoring equipment.

At the end of the study, the relationship between coal dust concentration and some coal properties and cutting operating parameters were expressed by using four different regression equations. Also it has been found that tip speed of saw, fixed carbon, ash and huminite content, vitrinite reflectance and hardgrove grindability index are very important parameters in coal dust generation.

Keywords: Respirable Coal Dust, Dust Generation, Real Time Dust Sampler, Coal Dust Diseases, Coal Cutting Operation.

ÖZ

BAZI LİNYİTLERİN LABORATUVAR KOŞULLARINDA OLUŞTURDUĞU TOZLARIN İZLENMESİ VE MODELLENMESİ

Karakaş, Ahmet

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Teknolojik gelişmeler kömür madenciliğinde iş güvenliğini artırmış olmasına rağmen, yüksek oranda toz oluşumu hala önemli bir problem olarak karşımıza çıkmaktadır. Bu tez çalışmasının amacı, madenlerde kömür kesim işlemi sırasında ortaya çıkan toz miktarı ile kömürün bazı önemli yapısal özellikleri ile kömür kesim parametrelerinin arasındaki ilişkinin değişik toz tanecik boyut aralıklarında laboratuvar koşullarında incelenmesidir. Bu amacın gerçekleştirilmesi için, laboratuvar deneylerinde altı adet farklı linyit numunesi kullanılmıştır.

İki adet deney düzeneği kömür numunelerinin testere ile kesilerek toz oluşturmasına olanak verecek şekilde düzenlenmiştir. İlk deney grubu, büyük kömür kesme düzeneğinde üç adet farklı çaptaki testere kullanılarak, üç farklı toz tanecik boyut aralığında toz toplanarak gerçekleştirilmiştir (0-2.5 µm, 0-5 µm and 0-10 µm).

İkinci deney grubu, küçük ölçekli kömür kesme düzeneğinde tabla ilerleme hızları ve kömür kesme testere çevresel hızları değiştirilerek yapılmıştır. Bu deney grubunda tek bölgeye ait numuneler kullanılmış olup toz örneklemesi sadece 0-10 mikron aralığında 30 cm çaplı testere kullanılarak gerçekleştirilmiştir.

Bu çalışmada, linyit numunelerinin yapısal özelliklerinin belirlenmesi amacıyla, numunelerin kısa analizleri, petrografik analizleri ve öğütülebilirlik analizleri (Hardgrove öğütülebilirlik analizleri) yapılmıştır. Deneyler sırasında toz yoğunluklarının ölçülmesi için Microdust Pro gerçek zamanlı toz görüntüleme cihazı kullanılmıştır.

Çalışmanın sonunda, toz yoğunluğu ile kömürün bazı özellikleri ve kömür kesme parametreleri arasındaki ilişki dört farklı regresyon eşitliği kullanılarak tanımlanmıştır. Ayrıca, toz oluşumunda çevresel kömür kesim hızı, kömürün sabit karbon içeriği, kül içeriği, huminit içeriği, maksimum vitrinit yansıma değerleri ile Hardgrove öğütülebilirlik indeks değerlerinin çok önemli rol oynadıkları tespit edilmiştir.

Anahtar Kelimeler: Solunabilir Kömür Tozu, Toz Oluşumu, Gerçek Zamanlı Kömür Tozu Örnekleyici, Kömür Tozu Kaynaklı Hastalıklar, Kömür Kesme İşlemi

To My Family

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CHAPTER 1

INTRODUCTION

1.1 General

Today, world energy demand rises with rapid population growth and this fact increases the importance of coal as a primary energy source. Finkelman et al. (2002) considered about this subject that coal will be a dominant energy source in both developed and developing countries for at least the first half of the 21st century.

With the help of advanced technologies, modern mining methods are started to be used and these technologies increase the unit coal production in this sector. These developments about production means that the potential for increased dust exposure is greater today than it was ten years ago (Güyagüler and Karakaş, 2002).

Prolonged exposure to coal dust during mining activities increases the risk of developing "Coal Workers Pneumoconiosis" (CWP) and some other diseases. This situation affects the health of the workers negatively and it should be prevented or decreased by taking necessary precautions. In combating mine dust, knowledge about the relations between its main sources and amount of dust generation will help to take the appropriate precautions for reducing the dust hazard.

Therefore, understanding the relationship between coal seam properties, some operating parameters and dust generation is a crucial subject to prevent the harmful effects of the coal dust.

1.2 Statement of the Problem and the Thesis Objective

Health researchers stated that a relationship exists between the dust generation and type of the coal seam. However, as the structure of the coal is very complex, it is very difficult to define this relationship. Therefore, some of the reseachers found a strong positive correlation while the others found a weak one about the relationship of the same property of coal with dust generation.

Since coal is not a homogeneous substance, different types of factors should be considered in order to understand the mechanism of the coal dust generation. For example, some studies focused on the effect of coal rank on dust generation. During these studies, laboratory coal comminution procedures were applied and they found a significantly positive correlation between the coal rank and the amount of respirable sized particles found in the product (Moore and Bise, 1984; Baafi and Ramani, 1979). On the contrary, underground and laboratory studies conducted by the former U.S. Bureau of Mines (USBM) in the late 1980s and early 1990s showed an opposite correlation between the coal rank and airborne dust generation compared to previously established coal rank and fines production relationships. Bennett et al. (1979) found that there are three to five times more fold differences in prevalence of the Coal worker pneumoconiosis between coal mines having the same rank of coal. These examples show that investigating the effect of only one factor is not sufficient to understand the underlying reasons about generation of the coal dust.

Physical, chemical and petrographical properties of coal should be taken into consideration in order to understand the structure of the coal dust generation. In addition to these, since cutting action of the shearer is the most important dust source, cutting action of the saw was used to generate dust during the experiments under laboratory conditions. Most of the studies about this subject were conducted by using crushing and grinding process in order to measure the dust concentration in laboratory conditions and they applied the size analysis to the product of these processes. However, in this study, dust concentrations were measured by using airborne dust particles.

However, studying the effect of all these properties as a whole is a very complex and difficult process. Therefore, some coal seam properties and cutting operating parameters (tip speed of saw and table advancing velocity) should be selected to obtain reliable results from the measurements under laboratory conditions in this thesis.

The objective of this thesis is to find the relationship between some of the important physical, chemical and petrographical properties of coal and cutting parameters with dust concentration and developing equations for determining the dust generation potential of any lignite seam. These equations would cause a priori information about the dust potential of the coal seam. By the help of these results, dust control technologies can be used more efficiently.

1.3 Methodology of the Thesis

Six different lignite coal samples (Bursa, Tunçbilek, Soma, Seyitömer, Beypazarı (upper and lower seam)) were used in this study in order to investigate the effect of the properties of coal on dust generation rates. The reason for this selection is that lignite is the most important domestic energy source of Turkey. Furthermore, there are a lot of lignite mines all over Turkey, therefore, practical applications of the results of this study are expected to be applied more easily to prevent or decrease the harmful effects of dust.

In order to generate the dust in laboratory conditions, cutting action of the saws were used. Experiments were conducted in two different systems which were called large and small scale saw system.

Three saws having three different diameters were used at the large scale saw system. Real time dust monitoring equipment was used in order to measure the dust concentration values. This equipment has the ability to record the dust concentrations in each second. With this equipment, three different particle size poly urethane filters can be used. Since harmful effect of the dust on human health is directly related to the size of the dust particles, this property of the dust sampler provided valuable information about the degree of the harmfulness of the coal.

One lignite sample was used in the small scale saw system experiments. This system provided different table advancing velocity and tip speed facilities during the cutting of the coal samples, and by use of these parameters, relationship between coal dust generation and table advancing velocity and tip speed of saw were investigated.

In order to characterize the coal samples, Hardgrove grindability index values, some of the petrographical (maceral and lithotype content, vitrinite reflectance) and chemical properties (ash, moisture, fixed carbon and volatile matter content) were determined. Moreover, tip speed values were calculated for each of the saws having different diameters. At the end of the thesis, correlation analysis were applied to understand the relationship between these variables. After this process, linear and non-linear regression analysis were used and as a result of these applications, four different regression equations were obtained in order to explain the relationship between lignite coal sample properties, tip speed of saw, table advancing velocity and dust particle size with dust concentration values measured under laboratory conditions. These equations give the information about the dust generation potential of the lignite seam and this will provide the selection of the most suitable dust control method in lignite mines.

1.4 Outline of the Thesis

In this study; following the introductory chapter, in Chapter 2, the definition of the dust is given in detail with its important properties. Classification of dust according to its harmfulness is also stated. Another information mentioned in this chapter is the consequences of the exposure of dust in relation to the human health. After giving detailed information about coal dust related dieseases, a comprehensive explanations about the dust measuring equipments and principles are presented.

Chapter 3 presents the detailed explanations of the coal properties and their relationships with dust generation rates. In this chapter, descriptions of the petrographical, chemical and grindability properties of coal are given.

Chapter 4 gives the comprehensive information about the properties of the expermental set-up and also provides detailed information about the equipments used during the experiments. The information about the analysis of the coal samples are also given in this chapter.

Chapter 5 includes the results and discussion parts of this study. Some of the physical, chemical and petrographical properties of the samples are given in this chapter. Relationship between the different coal properties and tip speed of saw, table advancing velocity with the dust concentration are explained in detail in Chapter 5. At the end of this chapter, four different model are developed by using multiple regression analysis.

The major conclusions drawn from this study along with the recommendations for further studies are summarized in Chapter 6.

CHAPTER 2

MINE DUST

2.1 Definition of Dust

“Dust” in a geological context which generally refers to the solid particles emitted into the air directly from the earth’s crust by wind or human activities (Gill et al., 2006). Dust also can be defined as finely divided solid particles in the air (Sengupta, 1990). According to the International Standardization Organization (ISO 4225 - ISO, 1995), dust is small solid particles, conventionally taken as the particles below 75 µm in diameter, which settle out under their own weight but which may remain suspended for some time (WHO,1999). Glossary of Atmospheric Chemistry Terms (IUPAC, 1990) define the dust as " Small, dry, solid particles projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shovelling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1 to 100 µm in diameter, and they settle slowly under the influence of gravity."

Vincent (1995) defined the dust as an aerosol consisting of solid particles made airborne by the mechanical disintegration of bulk solid material with different sizes. Figure 2.1 shows the typical aerosols and aerosol particles and health related definitions of aerosols with their size range.

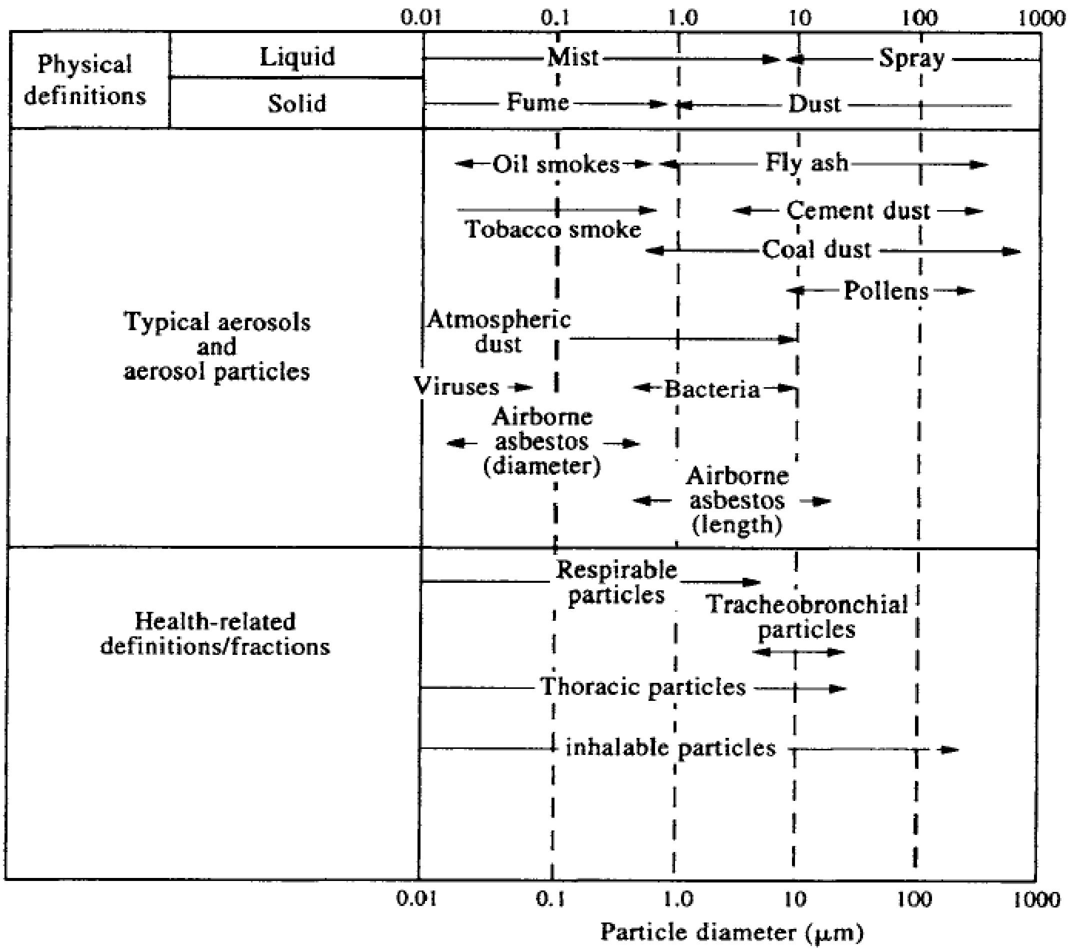

Figure 2.1 Summary classification of aerosols (Vincent 1989, in Vincent,1995)

Dusts can be classified acording to their harmful physiological effects. The following shows different types of dusts in the order of decreasing harmfulness in each category (Sengupta,1990):

- Fibrongenic Dusts (harmful to the respiratory system)
    - Silica
    - Silicates (talc, asbestos, mica)
    - Beryllium ore
    - Metal fumes
    - Tin ore
    - Iron ore
    - Coal

- Carcinogenic Dusts (cancer-causing)
  - Radon daughters
  - Asbestos
  - Arsenic
- Toxic Dusts (poisonous to human organs)
  - Arsenic
  - Lead
  - Uranium
  - Nickel
  - Tungsten
  - Silver
- Radioactive Dusts
  - Uranium ore
  - Thorium ore
- Nuisance Dusts (few adverse effects)
  - Limestone
  - Gypsum
  - Kaolin

Dust particles are usually divided into three classes; particles greater than 10 micrometers, which settle according to the laws of gravity, i.e., with increasing velocity in still air. Particles between 0.1 to 10 micrometers, which in still air settle at a constant velocity that can be calculated by Stoke's law (the uniform settling velocity depends on particle size and density, viscosity of the medium, and acceleration due to gravity). Particles between 0.01 and 0.1 micrometers, which do not settle but diffuse in the air and remain colloidal state (Sengupta,1990).

A dust cloud consisted of particles less than 5 micrometers in size is not visible to the naked eye. It cannot be seen in the strongest beam of light at underground but appears as motes in a beam of sunlight.

Vincent (1995) stated that degree of the harmfulness of the dust on human health depends on the different factors, including: (a) particle size distribution (which governs how the aerosol enters the body by inhalation, and how it penetrates into and is subsequently deposited in the respiratory tract), (b) airborne concentration and (c) morphology, mineralogy and chemical composition (which govern the subsequent fate and biological responses to the presence of the particles in contact with vulnerable tissue).

Any dust, if present in excessive quantities and inhaled for a sufficiently long time, can cause physiological damage. Sengupta (1990) also listed the factors, which determine the harmfulness of any dust as follows: composition, particle size, concentration in mine air, exposure time, and susceptibility of the exposed individual.

Mineralogical and chemical composition are also very important. For example, free silica is more damaging than combined silica. The surface energy of the particles can be a determining factor, and solubility is a very important variable in toxic dusts.

Dust concentration in mine air is expressed either in terms of the number of particles per unit volume of air or weight of particles per unit volume of air. On the basis of number, dust concentration is specified as millions of particles per cubic foot of air or as particles per cubic centimetre of air. On the basis of weight or on a gravimetric basis, dust concentration is measured as milligrams per cubic meter of air (mg/m^3) (Sengupta,1990).

Size of the dust particles is very important parameter with regards to their adverse effects on human respiratory system. Therefore, in order to classify the dust particles according to their size, one measurement system should be used especially for the particles having different shapes and densities with a single unit. At this point, aerosol scientists use the term "aerodynamic diameter”. This term can be defined as the diameter of the sphere particle having a density of $1gr/cm^3$ that has the same inertial properties (terminal settling velocity) in the gas as the particle of interest (Figure 2.2). Briefly, terminal settling velocity is the velocity of a falling particle when the gravitational force downward is balanced by the air resistance force upward.

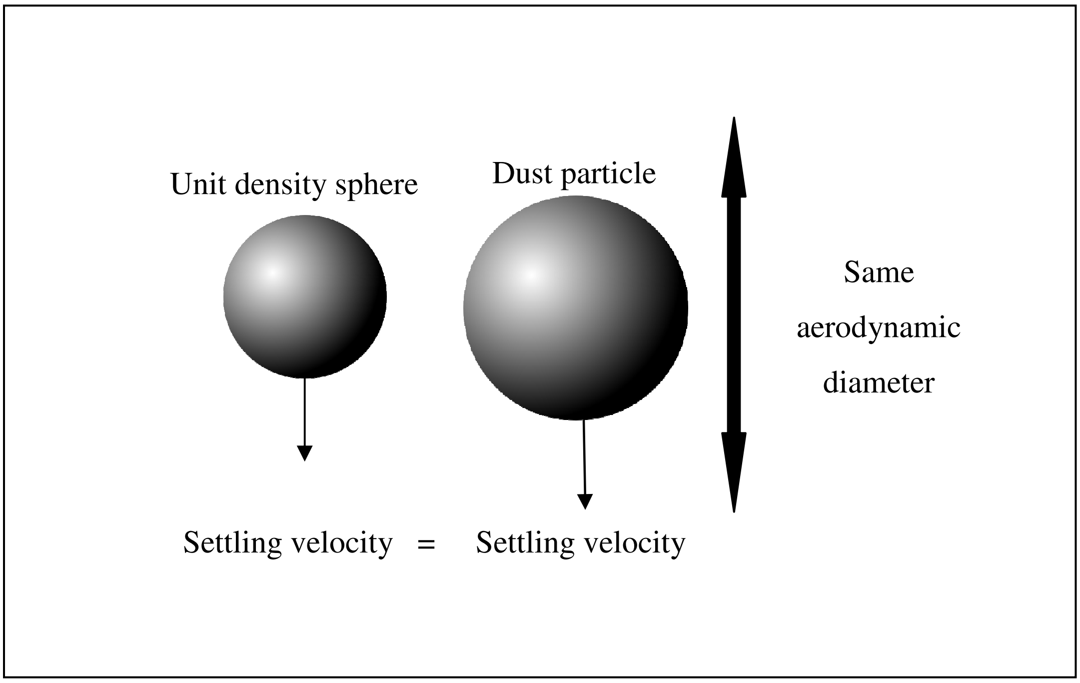

Figure 2.2 Particles having the same aerodynamic diameter

In aerosol science, to define all particles that are suspended in the air, the term "Particulate matter" (PM) is used. Particles having an aerodynamic diameter of less than or equal to 10 micrometers and 2.5 micrometers can be shown as PM_{10} and $PM_{2.5}$ respectively. In general, particles ranging in size between $PM_{2.5}$ and PM_{10} are called coarse particles. Similarly, fine particles can be described as the particles having an equivalent diameter of between 0.1 µm and 2.5 µm ($PM_{0.1} \leq$ fine particles $\leq PM_{2.5}$). Ambient particulate matter size distributions can be seen in Figure 2.3 As the particles are so small and fine, they can remain suspended in the atmosphere for a very long periods. These fine particles are capable of scattering sunlight, resulting in reduced visibility over long distances.

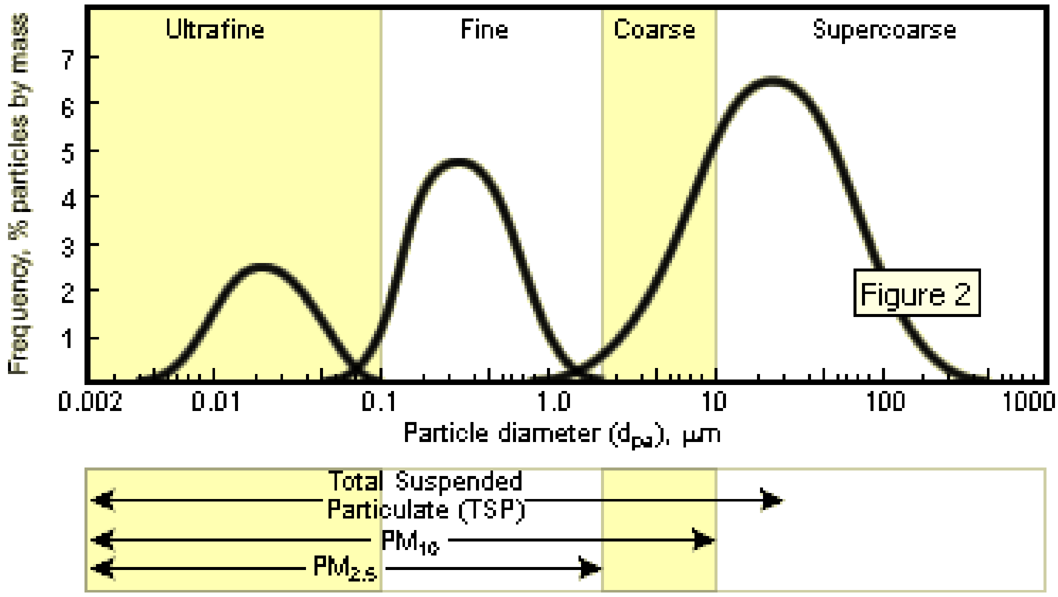

Figure 2.3 Ambient particulate matter size distributions (www.epa.gov)

The exact point where a particle deposits in the human respiratory tract depends on the size of the particle. In this respect, human respiratory system can be divided into three as follows: Extrathoracic region, Tracheobronchial region and Alveolar region (Figure 2.4).

Effect of the dust particles on human health is directly related with their accumulation and penetration rates at human respiratory system (Figure 2.5). Irritation can occur everywhere along the respiratory system because of the dust occurence but acute damage mostly can be seen at the lower respiratory system where clearence system of the lung is located.

Aerosol scientists use some terms related with the size of the particles and their deposition points at human respiratory tract. Most important terms are: respirable dust, inhalable dust and total dust. Respirable dust means particles that are small enough to penetrate the nose and upper respiratory system and deep into the lungs.

The American Conference of Governmental Industrial Hygienists (ACGIH), the International Organization for Standardization (ISO), and the European Standards Organization (CEN) have reached an agreement on definitions of the respirable and inhalable fractions ((ACGIH, (1999), in WHO (1999)); ISO, 1995; CEN, 1993; ICRP, 1994). According to this agreement, the respirable dust is the fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs. United States Mine Safety and Health Administration (MSHA) defines respirable dust as the fraction of airborne dust that passes a size-selecting device as can be seen at Table 2.1. Especially, the smaller particles may penetrate to the alveolar region of the lung , the region where inhaled gases can be absorbed by the blood. In aerodynamic diameter terms, only about 1% of 10μm particles get as far as the alveolar region, therefore 10 μm is usually considered the practical upper size limit for penetration to this region. Maximum deposition in the alveolar region occurs for particles of approximately 2 μm aerodynamic diameter. Most particles larger than this are deposited further up the lung (WHO,1999).

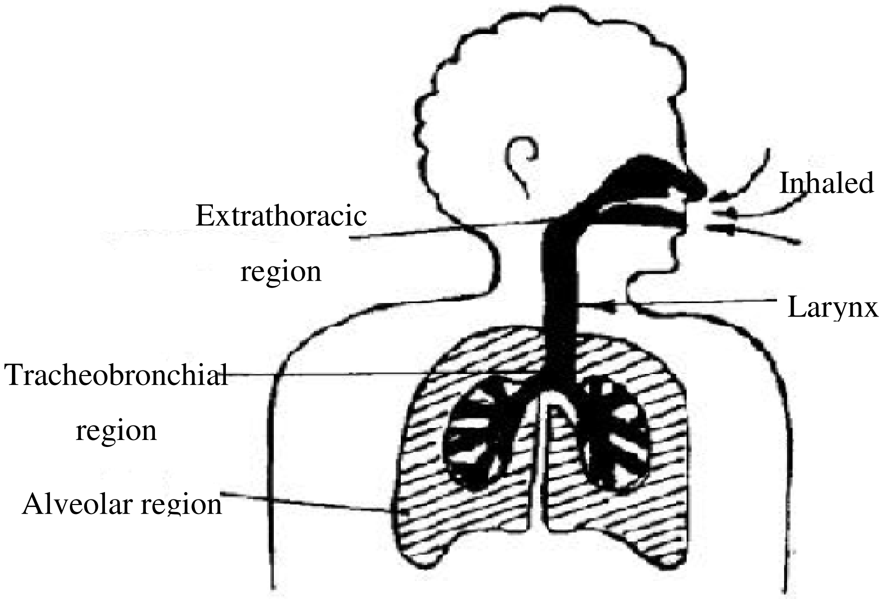

Figure 2.4 Schematic representation of the human respiratory tract (WHO, 1999)

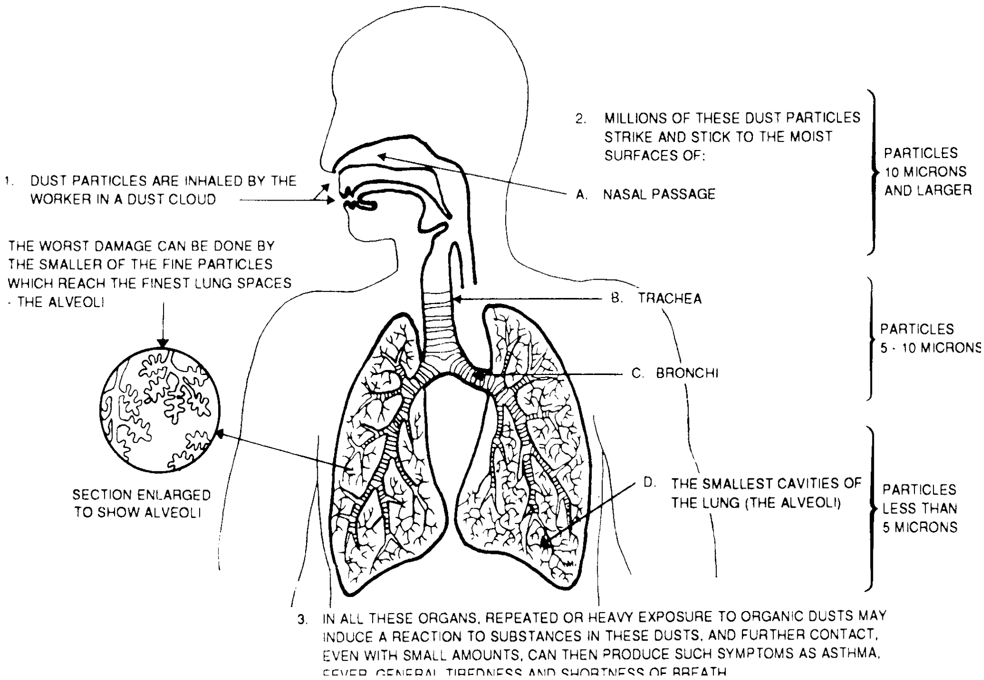

Figure 2.5 Dust particles and human respiratory system (Choiniere and Munroe, 1995)

For smaller particles, most deposition mechanisms become less efficient, so deposition is less for particles smaller than 2 µm until it is only about 10-15% at about 0.5 µm. Most of these particles are exhaled again without being deposited. For still smaller particles, diffusion becomes an effective mechanism and deposition probability is higher. Deposition is therefore a minimum at about 0.5 µm (WHO, 1999). In Turkish regulations, respirable dust is defined as the particles having an aerodynamic diameter between 0.5 µm and 5 µm. During this study particles having an aerodynamic diameter smaller than 5 micrometers was accepted as the respirable dust particle.

Table 2.1 MSHA respirable dust definition fractions that passes a size-selecting device (Cash, 2003)

Aerodynamic Diameter (µm) (Unit density spheres)	**Percent passing selector**
2.0	90
2.5	75
3.5	50
5.0	25
10.0	0

Another two definitions of respirable dust are accepted by U.S. Atomic Energy Commission (AEC) and British Medical Research Council (BMRC). Both of them approximate the dust deposition in the nonciliated portions of the lung. The first one, resulting from work performed by the U.S. Atomic Energy Commission (AEC), is defined by the curve labeled AEC in Figure 2.6. The other definition for the respirable fraction of dust recommended by the British Medical Research Council is showed by the sampling efficiency curve labelled BMRC in Figure 2.6. The pulmonary deposition curve is also shown in Figure 2.6.

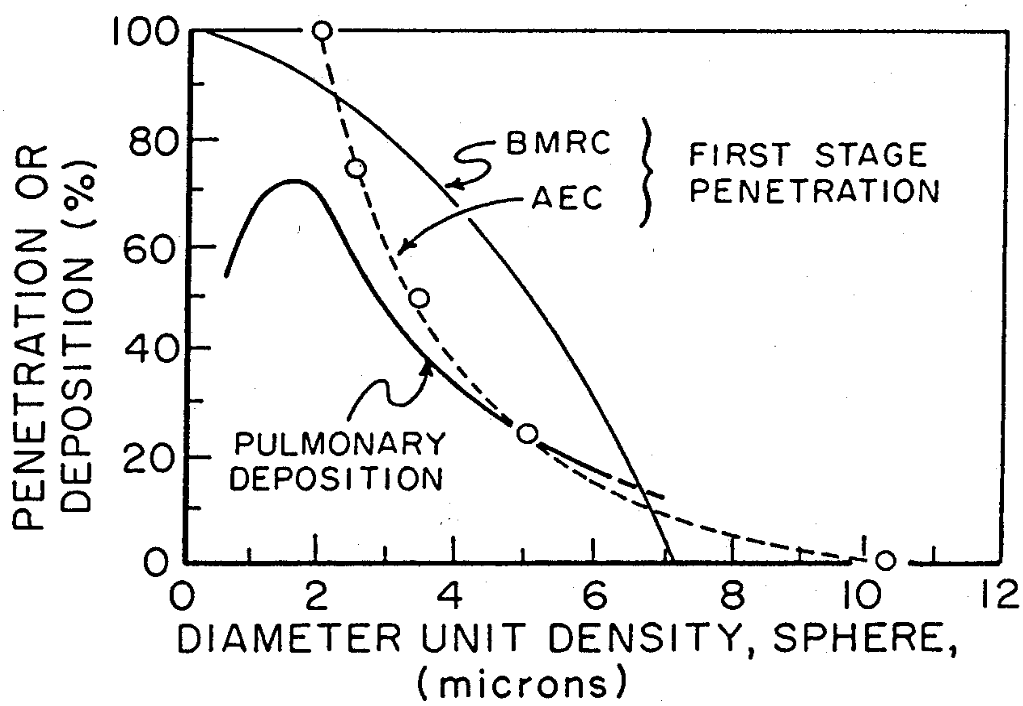

Figure 2.6 Pulmonary deposition curve and comparison of respirable dust criteria (Sengupta,1990)

In the work of Heyder et al. (1986) (in Martin and Finlay, 2006), they found that for given tidal volumes and flow rates, total respiratory tract deposition varied with aerodynamic particle diameter along well-recognized U-shaped curves. Kim and Hu (2006) studied the total respiratory tract deposition of fine sized particles and some of their findings related with the total deposition fraction and particle diameter can be seen in Figure 2.7. Park and Wexler (2008) studied the relationship between particle size and deposition fraction and they compared their results with two different early set models (Figure 2.8). They pointed out that lowest deposition rates were recorded for fine particles (0.1-1 μm) and relatively higher deposition rates for coarse (<3 μm) and ultra fine particles (< 30nm).

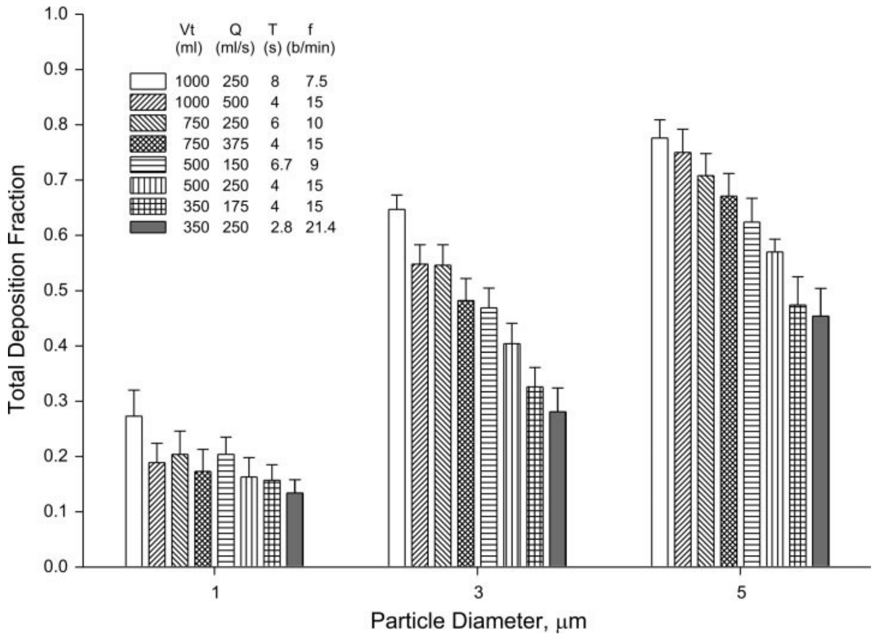

Figure 2.7. Total lung deposition fraction vs. particle diameter for 8 different breathing patterns in men (Kim and Hu, 2006)

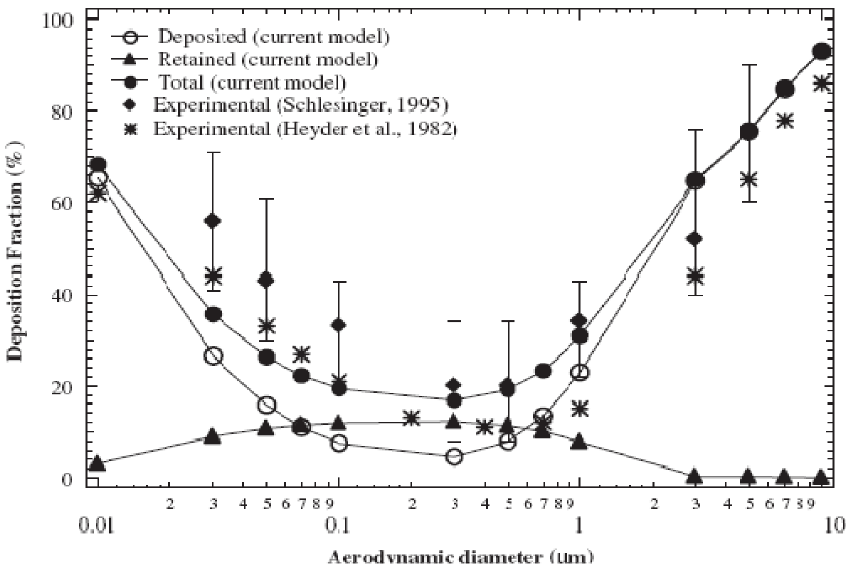

Figure 2.8 Comparison of model-derived total deposition fraction to measurements (Park and Wexler, 2008)

Another important definition is the inhalable dust. Inhalable dust is defined as the size fraction of dust which enters the body, but is trapped in the nose, throat, and upper respiratory tract. The median aerodynamic diameter of this dust is about 10 μm. ACGIH, ISO and CEN defined inhalable dust as fraction of a dust cloud that can be breathed into the nose or mouth. Total dust is the another critical term and includes all airborne particles, regardless of their size or composition (Table 2.2) (ACGIH, 1999a).

Table 2.2 The fraction of the airborne material which a sampler should collect where the inhalable fraction is on interest (ACGIH,1999a)

Aerodynamic Diameter (μm)	**Inhalable fraction (%)**
0	100
1	97
2	94
5	87
10	77
20	65
30	58
40	54.5
50	52.5
100	50

Exposure time is the another important parameter in relation to the effect of dust on human-being. The average time for development of silicosis has been found to be 20 to 30 years. In rare cases only has silicosis been diagnosed in less than 1 year of exposure. Susceptibility to pulmonary disorder is also a function of age and may differ person to person.

2.2 Coal Dust Related Diseases

Centuries before the Christian era, Hippocrates wrote of a lung disease common to those who mined in hard rock. He was obviously discussing silicosis. Silicosis among hard rock miners was certainly described by Agricola (1494-1555) in his “De Re Metallica” published in 1556. In additon to this, Paracelsus (1493-1541) also gave the first recordings of the occupational ill related mining activities. Other ancient writings indicate that the Egyptians were aware of this malady (Sengupta,1990). Meiklejohn (1951) stated that the term “pneumonokoniosis” was started to be used in 1866 and was shortened to “pneumoconiosis” in 1874. Likewise, the term “silicosis” was introduced in 1870 to define the pneumoconiosis resulting from silica (NIOSH, 1974). By 1907, chest X-rays were used to study lung disease in coal miners but their quality permitted only the detection of gross pathological changes until about 1930 (Meiklejohn, 1952). Figure 2.9 shows the time frame of the particle toxicology (Donaldson and Borm, 2007).

The medical community in Europe and the U.S. recognized the silica health hazard in the early 1900s. They were concerned about the health hazard of sandblasting in polishing shops, the efficiency of the exhaust systems, and the necessity to protect the sandblasters against dust hazard. Sandblasting, hardrock mining, and drilling are equally hazardous occupations. In 1966, the American Conference of Government Industrial Hygienists (ACGIH) made a recommendation on allowable silica levels in the workplace atmosphere (Sengupta,1990).

Fishwick (2008) stated that the site of damage within the lung is a function of both the size and the toxicity of the inhaled particles and generally particles with a median diameter of 0.5–10 μm can penetrate the alveoli, and those that are toxic to host cells (particularly macrophages) can cause permanent harm. Prolonged exposure to airborne respirable coal dust is responsible for the prevalence of Coal Workers' Pneumoconiosis (CWP), silicosis, bronchitis and emphysema. In addition to these illnesses, it causes also cancer, allergic responses and some of the lung diseases.

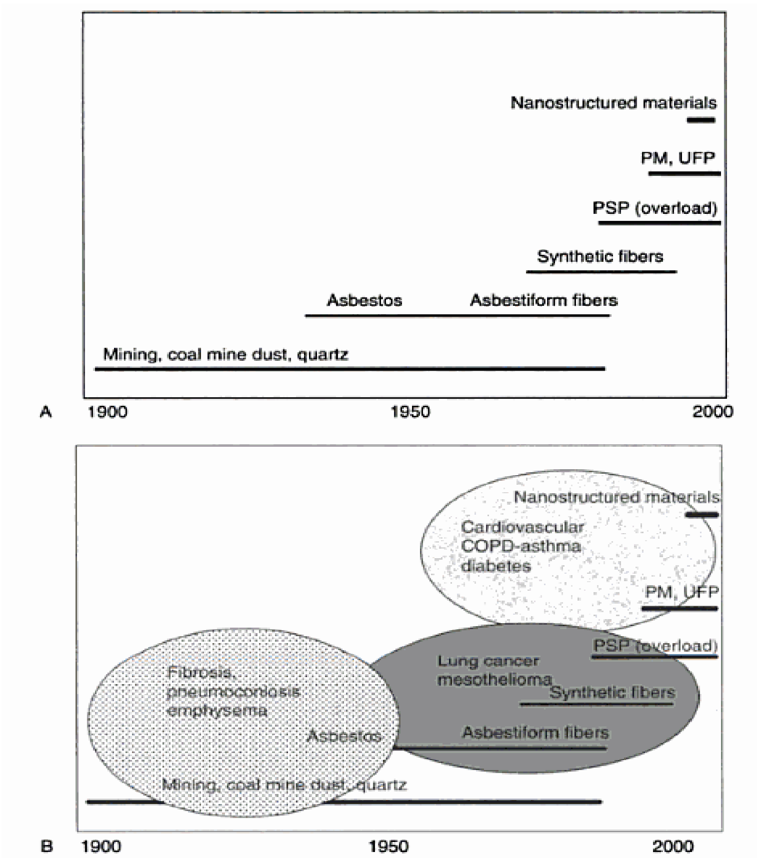

Figure 2.9 Part A: Time frame of particles driving particle toxicology, Part B: Particles along with the major outcomes that were studied (Donaldson and Borm, 2007)

2.2.1 Coal Workers’ Pneumoconiosis (CWP)

Inhalation of coal dust for continued and prolonged time periods results in coal workers’ pneumoconiosis (CWP), also referred to as black lung disease. In other words, accumulation of coal dust in the lungs and the reaction of lung tissue to the present of that dust causes this type of pneumoconiosis (Sengupta, 1990). Seaton et al. (1981) stated that quartz exposure causes the development and rapid progression of the coal workers' pneumoconiosis.

Black lung was first recognized as a disease of British coal miners in the mid-17th century. The term “pneumoconiosis” (“dusty lung”) was introduced in the 1870s. The cause of the disease in coal miners was first thought to be due to silica, until studies in the United Kingdom showed that exposure to coal dust containing very little silica could also lead to CWP. Diagnosis of CWP is usually based on the findings from x-rays and a history of working with coal (usually for 10 or more years). Among a group of people with similar exposures to coal dust, some may develop CWP and some may not. Factors that may contribute to this are differences in the effectiveness of lung clearance mechanisms, differences in the auto-immune reaction in the lung tissue and smoking (Government of Alberta web page). Progression steps of the coal workers’ pneumoconiosis in lungs can be seen in Figure 2.10.

Karol et al. (1979) studied the effect of the coal dust on respiratory system of the animals and they found that approximately 22% of the live macrophages from coal-exposed animals contained visible coal dust particles as determined by microscopic examination.

Simple CWP is characterized by development of coal macules, a focal collection of coal dust particles with a little reticulin and collagen accumulation. These lesions may be visible as small opacities (less than 1 cm in diameter) on X-rays (Hathaway et al., 1991).

Complicated CWP is characterized by lesions consisting of a mass of rubbery well defined black tissue that is often adherent to the chest wall. This is associated with decrements in ventilatory capacity, low diffusing capacity, abnormalities of gas exchange, low arterial oxygen tension, pulmonary hypertension, and premature death. The disease may progress after the cessation of exposure. In X-ray examinations, opacities greater than 1 cm in diameter may be observed (United States Occuppational Health and Safety Administration Web Page). Complicated CWP usually develops in miners already affected by simple CWP but it may also develop in miners with no previous radiographic evidence of simple CWP.

2.2.2 Silicosis

Existence of silica formation is another important parameter for human health. Especially, rock structures that contain coal have crystalline silica formation. Quartz, cristobalite, and tridymite are three forms of crystalline (free) silica; quartz, however, is the most common. Cristobalite and tridymite have a different crystalline structure than quartz and are generally considered to be more harmful biologically (Cash, 2003).

Cristobalite and tridymite are thermally altered forms of quartz. They may be present in areas where substances containing quartz are heated, such as in refractories, sintering, calcining, or heat expansion. Since these two substances are not detected in routine quartz analysis, mine operators should request a special analysis for cristobalite or tridymite if either of these silica materials are suspected to be present in the dust (Cash, 2003).

Therefore, overexposure to respirable quartz dust can lead to the development of silicosis, a debilitating and potentially fatal lung disease (Schatzel, 2009). Although silicosis is one of the oldest occupational diseases, it continues to be a one of the major cause of morbidity and mortality all over the world.

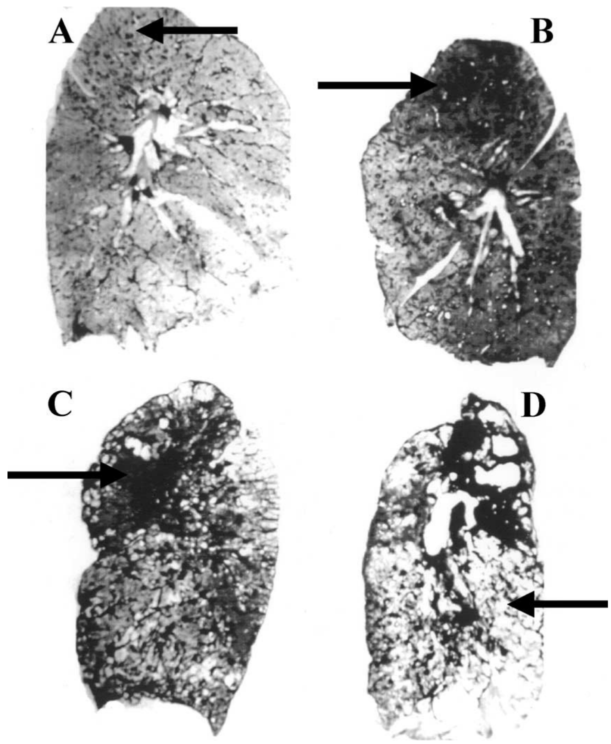

Figure 2.10 Different steps of coal workers' pneumoconiosis in lungs (Finkelman et al., 2002)

Silicosis is a diffuse pulmonary fibrotic disease that ensures from an extensive and prolonged exposure to free crystalline silica dust. Inhalation of dust containing crystalline silica (alpha-quartz or silicon dioxide) or its polymorphs (tridymite or cristobalite) is the primary etiologic agent of this preventable yet irreversible disease. This lung disease is caused by the inhalation and deposition of respirable crystalline silica particles (i.e., particles <10 μm in diameter) (Ziskind et al., 1976; IARC, 1987). Workers exposed to silica dust are often exposed to asbestos as well, and many develops asbestos-related respiratory diseases. Silicosis treatment is extremely limited considering a lack of cure for the disease. However, like all occupational respiratory ailments, it is 100 % preventable if exposure is minimized (Government of Alberta web page).

Important parameter related with the occurence and progression of the silicosis is the amount of the respirable silica-containing dust and the percentage of respirable silica in the total dust in the working environment. Other important factors are (NIOSH,2002):

1. the particle size,
2. the crystalline or noncrystalline nature of the silica,
3. the duration of the dust exposure, and
4. the varying time period from first exposure to diagnosis (from several months to more than 30 years) (Banks,1996; Kreiss and Zhen 1996; Hnizdo and Sluis-Cremer 1993; Hnizdo et al., 1993; Steenland and Brown 1995a; ATS 1997, in NIOSH,2002).

Mossman and Churg (1998) and Heppleston (1994) have reviewed the experimental evidences supporting the influence of above mentioned issues. A worker may develop one of the three types of silicosis, depending on the airborne concentration of respirable crystalline silica:

1. chronic silicosis, which usually occurs after 10 or more years of exposure at relatively low concentrations,

2. accelerated silicosis, which develops 5 to 10 years after the first exposure,

3. acute silicosis, which develops after exposure to high concentrations of respirable crystalline silica and results in symptoms within a period ranging from a few weeks to 5 years after the initial exposure (NIOSH, 1996b; Parker and Wagner 1998; Ziskind et al. 1976; Peters, 1986 in NIOSH, 2002).

2.2.3 Mixed Dust Pneumoconiosis

In coal mining, particularly surface coal mining, a worker is subjected to a mixture of the different types of dusts during the working time rather than to silica alone or other type of dusts alone. If crystalline silica is deposited with less fibrogenic dusts such as iron oxides, kaolin, mica and coal, "mixed-dust lesion" is formed. Cotes and Steel (1987) stated that except in the case of acute silicosis, the chest X-ray alone cannot show whether changes consistent with pneumoconiosis have resulted from carbonaceous dust or silica. This means that without detailed examination of the lung and knowledge of the exposure history, a chest X-ray showing pneumoconiosis in a coal miner may represent CWP, silicosis or mixed-dust pneumuconiosis.

2.2.4 Bronchitis-Emphysema

Another health disease connected with the inhalation of the coal dust is the chronic bronchitis. Barnhart (1994) defined the emphysema as the abnormal, permanent enlargement of air spaces distal to the terminal bronchiole, accompanied by destruction of their walls. Exposure to coal dust is associated with an increased risk of focal emphysema, which is usually associated with the presence of pneumoconiosis and centrilobular emphysema, can occur in the absence of pneumoconiosis (Rom, 1992).

2.3 Occupational Exposure Limit of Coal Dust

Occupational exposure limit can be defined as the airborne concentration of a gas or particle to which most workers can be exposed on a daily basis for a working lifetime without adverse effect. Therefore, exposure limit values are also very important because health hazards due to coal dust is directly related with these values. Threshold limit values (TLV) for harmful dusts change from one country to the other. Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists accepted 2.4 mg/m^3 and 2 mg/m^3 as threshold limit value for respirable coal dust which contains silica less than 5 percent during 8-hour workday respectively in U.S.A.

If contains more than 5% quartz value, respirable dust can be found by using equation 2.1,

$$TLV - TWA = \frac{10\, mg/m^3}{(\%\ respirable\ quartz + 2)} \tag{2.1}$$

According to the Turkish regulations, permissible exposure limits are defined according to coal dust quartz content. If SiO_2 content is higher than 5% in mining environment, threshold limit value for coal dust can be found by using equation 2.2 (Turkish dust regulation,1990):

$$TLV = \frac{25}{(\%\ SiO_2)}\ mg/m^3 \tag{2.2}$$

If SiO_2 content is smaller than 5% in mining environment, threshold limit value for coal dust is taken as 5 mg/m^3.

The work of Macejewska (2008) summarized the methods used for assessment of exposure to crystalline silica as adopted in different countries and investigated occupational limit values in force in almost 40 countries (Table 2.3).

Table 2.3 Occupational exposure limits for free crystalline silica (Macejewska, 2008)

Organization/country	Exposure limit and interpretation	Crystalline silica form	Dust fraction	Limit value (mg/m^3)
The American Conference of Governmental Industrial Hygienists/USA	Threshold limit value (TWA-8h/day-40h/week)	Crystalline silica:α –quartz cristobalite	Respirable dust	0.025
National Institute for Occupational Health and Safety/USA	Recommended exposure limit (TWA-10h/day and 40h/week)	quartz cristobalite tridymite	Respirable dust	0.05
Occupational Safety and Health Administration/USA	Permissible expsure limit (TWA-8h/day-40h/week)	Dust content quartz	Respirable dust	$\frac{(10mg/m^3)}{(\%SiO_2+2)}$
			Total dust	$\frac{(30mg/m^3)}{(\%SiO_2+2)}$
		Dust content Cristobalite tridymite	Respirable dust	½ value of the quartz
			Total dust	½ value of the quartz
Denmark	Limit value	quartz	Respirable dust	0.1
			Total dust	0.3
Great Britain	Workplace exposure limit (TWA-8h)	Crystalline silica	Respirable dust	0.1
Russia	Occupational exposure limit	quartz	Total dust	1
	Short term exposure limit			3
	Short term exposure limit	Cristobalite	Total dust	1

2.4 Dust Measuring Principles

Different types of dust sampling devices are used in mining and other industries. These equipment can be classified according to the physical bases of operation as follows (Akkoyunlu, 1974):

- Filtration devices
- Sedimentation
- Cyclones
- Scrubbing
- Precipitation by impact
- Electrostatic precipitation
- Thermal precipitator
- Gravimetric samplers
- Light scattering instruments

2.4.1 Filtration Devices

These instruments are composed of aspirator, filters and air flow meters. The dusty air is sucked along a vertical or horizontal channel, and the particles are seperated according to their settling velocities.

2.4.2 Sedimentation Cells

In this method sample air is collected in a closed cell and then dusty air is sent to settle on a microscope cover slip or a slide.

2.4.3 Cyclones

This type of instruments use centrifugal force to remove dust. Cyclones are designed to collect a pre-defined size range and reject all particles larger than the upper limit. In typical cyclones, there is one pre collector unit and the air enters this collector tangentially at its side and swirl around inside. Particles having an aerodynamic diamater above the predetermined upper size limit are sent to the cyclone walls and collected at its base. Other particles leave through the central exit in the top of the cyclone and the air is filtered to collect the dust. These cyclones are usually of small sizes, from 10 mm to 50 mm in diameter. Calibration of the cyclones is very important to obtain the predefined particle size (Akkoyunlu, 1974).

2.4.4 Scrubber Devices

In these instruments, the dust is collected in water or alcohol after impingement through a jet. The air is expired by a small pump or by an ejector and then passes through a wash bottle that contains a liquid with a low surface tension. After this process, the sample can be weighed after evaporation of the alcohol, or counted in a suspension that can be diluted or concentrated as needed.

2.4.5 Precipitation by Impaction

In this type of instruments, dust particles are collected when dust-laden air is blown on to a glass slide, which may or may not be covered with an adhesive by pump. The instruments of this type are the cascade impactor and the konimeters.

2.4.6 Electrostatic Precipitation

Under the influence of a powerful magnetic field, dust particles become ionized or electrically charged and tend to move towards the anode or the cathode according to the magnitude or sign of the charge. Sampling is generally done for gravimetric determinations but the instrument can be arranged to collect directly for counting.

2.4.7 Thermal Precipitation

The principal of operation of the thermal precipitator is to pass an aspired sample of the mine air around an electric resistance wire heated by a battery. The hot wire is surrounded by a thermal gradient and the dust in the air is deposited on two cold cover slips placed on either side of the wire. The dust collection efficiency for particles up to about 10μm diameter approaches 100%, provided that a critical velocity of the airstream past the hot body is not exceeded. After sampling, the cover glasses are suitably mounted on a standard microscope slide, placed on the stage of a high power, high-resolution microscope, under which the particles are counted. The volume of air sample is measured so that the number of particles of any size can be expressed in numbers per unit volume of air sampled. If the sample contains siliceous dust, the slides may be ignited and acid may be treated in order to remove carbonaceous and acid soluble particles. Results are usually reported as the number of parts per cubic centimetre (ppcc).

2.4.8 Gravimetric Dust Sampling

The instrument comprises basically a size selector, a filter holder and an electrically driven pump designed to pass certain quantity of air per minute. The size selector is a multi channel horizontal elutriator which is made from flat seperated to give channels of dimensions such that large particles fall to the base of the channel before reaching the end. At the end of the elutriator channels, there is a transfer hood and the filter holder. Small particles are retained by the filter from the drawn air by the pump. The instrument of this type is the MRE 113 A which has been developed at the Mining Research Establishment of the National Coal Board, in England (Figure 2.11). An electrically driven pump draws dusty air to be sampled through a filter disc at a rate of 2.5 litres per minute. This instrument samples respirable fraction of airborne dust. Therefore, dust collected on the filter is respirable dust. Elutriator of the sampler functions as a size selector before dusty air passes through filter paper. This size selector is a four-channel horizontal plate elutriator. Separation and area of plates should be carefully controlled so that every elutriator can provide identical performance (Sengupta,1990). It provides 50% collection of particles with falling speeds equal to that of 5 micrometers unit density spheres.

These instruments can operate throughout the shift. Respirable dust is collected on the filter. Before the operation, weight of the filter (clean) should be determined. After sampling, filter is weighted again (dust+filter). Difference between these values gives the weight of the dust. The amount of air that passes through the sampler is found by multiplying operation time (min), and volume of the air passed through sampler (lt/min). Knowing the amount of air passed through the sampler and the weight of dust collected on the filter, concentration of dust in terms of mg/m^3 can be calculated easily.

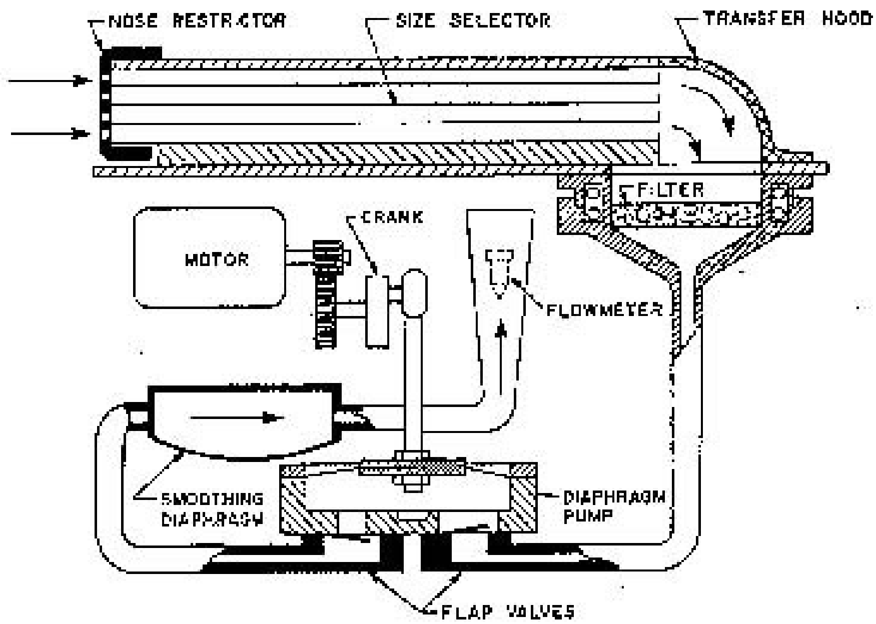

Figure 2.11 MRE gravimetric sampler (Sengupta,1990)

2.4.9 Light Scattering Instruments

In most of the sampling instruments, the sampled aerosol is collected in a form (e.g., on a filter) after which it may be assessed gravimetrically by weighing on an analytical balance or may be recovered for chemical analysis. Such instrumentation is suitable when time-averaged measurement can be justified. However, there are occasions where short term measurement is required; for example, where the aerosol in question is thought to be particularly hazardous or where an immediate alert to high concentrations is required; or monitoring is desired in order to examine the effects of adjustments in process or dust control (Vincent,1995). As mentioned before, in order to find the effects of the different properties of the coal and other parameters on the dustability of the coal, real time dust monitoring is more suitable than others. Since this monitoring equipment shows all dust fluctuations during the cutting action of the specimens, it gives the necessary information about the relationship between amount of dust occurred and the properties being investigated.

“Direct reading real time aerosol monitoring devices” have been developed and used in the mining industry. Lehocky and Williams (1996) stated some advantages of these devices over the traditional gravimetric samplers as follows: these devices provide real-time data; they are simpler to use; and in the long run they are less expensive to operate (i.e., do not require the time and expense of weighing individual filters).

In 1908, the German physicist G. Mie derived a theory to explain the behavior of light when normal Rayleigh scatter no longer applies. Many people have tried to explain the principles of Mie-Theory (forward light scatter) in layman’s terms, but the science is hard to follow. The Mie scattering calculations are so complex that large computers are required, particularly if the complex refractive index must be used, as for metallic scattering particles. For non-spherical particles even more complex approaches are required, and workers such as R. Gans have solved special cases such as ellipsoids and rod-shaped particles; even more complex mixtures of particles of different sizes. These solutions are important in the investigation of colloids, aerosols, smokes, smogs, and so on, where the particle sizes and shapes may be deduced from the light scattering behavior (Anon, 2005).

Figure 2.12 shows the principle of near forward light scatterring. The light source on the left of the Figure 2.12 represents an infrared beam of 880 nm wavelength that is passed through a number of lenses to collimate it. In clean air conditions, the beam is stopped by the light stop represented in black. As the beam passes through the sensing volume, where particulate is introduced, the beam is scattered by the particles. This is picked up by the photo detector, which amplifies the signal and converts it to a mass concentration.

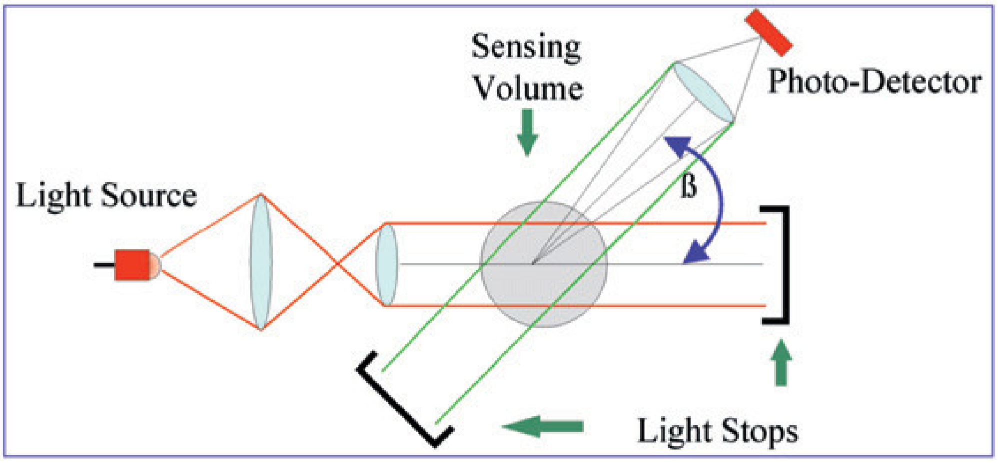

Figure 2.12 Principles of the near forward light scatter (Anon, 2005)

The narrow angle of scatter is represented by the angle β and is around 12 to 20° depending upon configuration. This reduces the amount of light scattered in the reflected component and instead concentrates on the diffracted and refracted components (Figure 2.13). The most important component is the diffracted light, which is the light "bending" around the object. Diffraction generally does not depend on particulate color or refractive index. The use of a narrow angle eliminates most of the uncertainty involved with differences in color or refractive index (Anon, 2005).

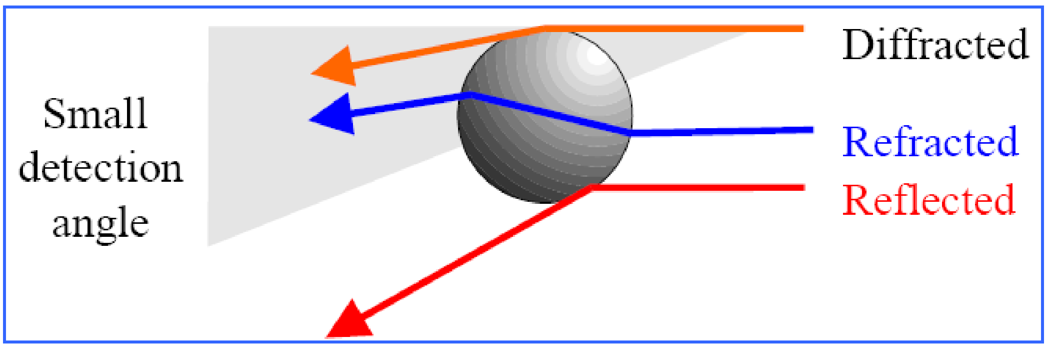

Figure 2.13 Simple illustration of narrow angle forward light scatter (Anon, 2005)

CHAPTER 3

SOME FACTORS EFFECTING THE DUST GENERATION POTENTIAL OF THE COAL

3.1 Effect of Coal Petrography on Dust Generation

In order to realize the coal dust occurence mechanism during mining activities, it is necessary to understand the structure of the coal formation and its properties. It should be noted that, as discussed earlier, there is a strong relationship between the structure of the coal and its negative effects on human health. At this point, the key question is “What is coal?”. Although, there is no exact definition of the coal, it can be described in a various ways. Coal can be defined as the accumulation of the vegetation by changing its physical and chemical properties (Crickmer et al., 1981). The other perspective, coal is the final result of the accumulated effort of the organisms, erosion, deposition of sediments and movement of the earth’s crust. On the basis of these definitions, it can be concluded that coal is the heterogeneous substance and it is composed of different structures. Although some of these structures, which are called lithotypes can be seen with naked eye, unfortunately some of them (macerals and minerals) can only be seen under microscope. Since impacts of them on coal dust generation are very important, they are investigated in detail in the following sub-sections of this study.

3.1.1 Lithotypes of Coal

Coal petrology is a science and deals with the structure, origin and classification of the coal while petrography is the systematic study of the coal components under microscopic conditions. Coal can be investigated at both macroscopic and microscopic level. At macroscopic level, one can easily see the bands and some structures on the surface of the lignite and bituminous coals. These structures can be characterized by some of the physical properties such as color, shape, brightness and so on. Stopes (1919) defined these visible bands as "lithotypes". According to Stopes (1935), there are four basic lithotypes in banded coals as follows: vitrain, clarain, durain and fusain.

3.1.1.1 Vitrain

Vitrain is a black, with brilliant, glassy lustre, conchoidal fracture, and a cubic cleavage. It is clean and structureless, and occurs in thin bands or lenses. The thickness of this formation ranges from a few milimeters to a few centimeters.

3.1.1.2 Durain

Durain is a greyish to dull black in color. It occurs in thick and thin irregular bands and breaks with irregular fractures (Toprak, 1997). Durain is thought to have formed in peat deposits below water level where only liptinite and inertinite components resisted decomposition and where inorganic minerals accumulated from sedimentation.

3.1.1.3 Fusain

It is commonly found in silvery-black layers only a few millimetres thick and occasionally in thicker lenses. Fusain is extremely soft and breaking readily into a fine dust. It soils the hands, and has a porous structure. Fusain is composed mainly of fusinite (carbonized woody plant tissue) and semifusinite from the maceral inertinite (high carbon, highly reflective) group. It closely resembles charcoal and it causes the generation of dust because of its soft structure.

3.1.1.4 Clarain

It is characterized by alternating bright and dull black laminae. The brightest layers are composed mainly of the vitrinite and the duller layers of the other maceral groups liptinite and inertinite. Clarain lacks its conchoidal frature and is less brillant than vitrain.

3.1.2 Maceral and Mineral Structure of Coal

Studies at microscopic level showed that coal formed extensively by organic compounds called macerals and lesser amounts of inorganic substances. Macerals are the microscopically recognizable individual constituents of coal and depending on their quantitative participation and their association, they control the chemical, physical and technological properties of a coal of a given rank (Sykrova et al., 2005). International Committee for Coal and Organic Petrology (ICCP) Handbook (1971) (in Toprak, 1997) defines the macerals as follows “they are microscopically recognizable individual constituents of coal”. Stope (1935) described the dome of the components of coal and suggested some of the macerals’ name and these names were adopted at the Heerlen Congress, held at Netherlands in 1935, called “Stopes-Heerlen Classification System”. Today, this system is the one of the widely used classification system for coal petrography. Another classification system used in coal petrography is the Thiessen system. Thiessen (1947) has observed coal with thin sections and named some of the coal entities as anthraxylon and attritus. Since both Stopes and Thiessen were using two different methods of analysis (Thiessen, transmitted light; Stopes, reflected light), the classification systems developed by each investigator varied considerably.

In the lignite and bituminous type of coal, there are three basic groups of macerals, which are; the vitrinite (huminite in lignites) group derived from coalified woody tissue, the liptinite group derived from the resinous and waxy parts of plants, and the inertinite group derived from charred and biochemically altered plant cell wall material.

3.1.2.1 Vitrinite-Huminite

The term “vitrinite” is introduced by the Stopes (1935) in order to describe parts of the medium rank coal that can only be seen under the microscope. This portion of the coal is generally the most abundant part of the coal. Vitrinite macerals are derived from the cell wall material of plants, which are chemically composed of the polymers, cellulose and lignin. These macerals have high amount of oxygen compared with other groups of macerals. Color of this maceral group is directly related to the rank of the coal. For the medium and high rank coals, its color changes between light grey to white and for the low rank coals, this group can be seen in dark grey (ICCP,1998). The low rank coals show a greater variety of macerals than higher rank coals. Maceral subgroups of the vitrinite according to ICCP system (1994) can be seen in Table 3.1.

Table 3.1. Classification of the vitrinite macerals according to ICCP-1994 (Sykrova et al.,2005).

Maceral Group	**Maceral subgroup**
VITRINITE	Telovitrinite
	Detrovitrinite
	Gelovitrinite

The huminites are regarded as the precursors of the vitrinites. The term “huminite” was first described in 1949 for a structural constituent of brown coals (now commonly termed lignites). The ICCP has used this term for a maceral group of lignites (brown coals) since 1970. This group of macerals has the color of dark to medium grey. Table 3.2 shows the maceral subgroups of the huminite. It has high oxygen and low carbon contents compared with liptinite and inertinite (Sykrova et al.,2005). It is very important to note that huminite and its submaceral groups are defined only for lignites and soft brown coals For subbituminous coals vitrinite nomenclature is used (Sykrova et al., 2005).

Table 3.2 Classification of the huminite macerals according to ICCP-1994 (Sykrova et al., 2005)

Maceral Group	**Maceral subgroup**
HUMINITE	Telohuminite
	Detrohuminite
	Gelohuminite

3.1.2.2 Liptinite (exinite)

The liptinite group macerals, which may be very important in methane generation, are derived primarily from spores, cuticles, resins, waxes, fats, and oils present in the original plant material (Table 3.3) (Ulery, 1998). These macerals are relatively rich in hydrogen and volatile matter and readily react during coalification. Liptinites are typically lower in oxygen than the vitrinites. Another feature of liptinite macerals is their fluorescence when irradiated with ultraviolet light (Ulery, 1998).

Depending on their rank, liptinites are highly reactive in chemical processes, and during carbonisation, liptinite enhances the fludity of coal. The outstanding petrographic feature of the liptinite group of macerals is that they all have a reflectance that is lower than the vitrinite macerals in the same coal. This group of macerals is very sensitive to advanced coalification and the liptinite macerals begin to disappear in coals of medium volatile rank and are absent in coals of low-volatile rank. When the liptinite macerals are present in a coal, they tend to retain their original plant form and thus they are usually "plant fossils" or phyterals.

Table 3.3 Liptinite maceral group and its possible origin (Ulery, 1998)

<table>
<tr><th>Maceral Group</th><th>Maceral</th><th>Origin</th><th colspan="2">Apperance</th></tr>
<tr><td rowspan="7">LIPTINITE</td><td>Sporinite</td><td>Spore and pollen cell walls</td><td rowspan="4">Least bright medium to dark gray</td><td rowspan="4">Identified by morphological characteristics</td></tr>
<tr><td>Cutinite</td><td>Waxlike coating of leaves and stems</td></tr>
<tr><td>Resinite</td><td>Numerous material including primary resins, fats and oils</td></tr>
<tr><td>Alginite</td><td>Algae</td></tr>
<tr><td>Bituminite</td><td>Probably related to decomposition of algae, faunal plankton and bacteria</td><td rowspan="3">Usually black</td><td rowspan="3">Usually very dark, occasionally mistaken for mineral matter or fracture. Distinct organic origin seen by fluoresence identified by morphological characteristics.</td></tr>
<tr><td>Exudanite</td><td>“secondary” resinite formed during coalification, veinlets</td></tr>
<tr><td>Fluorinite</td><td>“secondary”resinite probably formed from plant oils during coalification, massive</td></tr>
</table>

3.1.2.3 Inertinite

This group of macerals can be found at different amounts in coal. Inertinite group macerals are also mainly derived from plant tissues but are the products of oxidation in the peat swamp prior to burial. The inertinite maceral group has the highest carbon and lowest hydrogen content and at the same time inertinites have the property of highest reflectance. They are chemically inert as compared with the other two maceral group.

According to the new classification system of inertinite (ICCP System 1994), the number of the inertinite macerals have changed from six to seven. At this point, the former maceral sclerotinite was replaced by two other maceral called funginite and secretinite (ICCP, 2001) (Table 3.4). Funginite consists of fungal remains only, whereas secretinite comprises inert residues that are similar to fungal sclerotia in their optical characteristics but are, in fact, oxidized and subsequently coalified plant excretions. Important macerals of the inertinite group, so named for their relatively inert behavior in the coking process, include fusinite, semifusinite, and micrinite. Fusinite is a charcoal-like substance usually formed by rapid charring and alteration of cell wall material (vitrinite) prior to, or shortly after, incorporation into the enclosing sediment. This charring may be a result of paleo-forest fires, and an abundance of this maceral may indicate relatively dry conditions. Semifusinite is a less altered maceral and represents material intermediate between vitrinite and fusinite. Micrinite is an atypical inertinite maceral because it generally does react during the coking process (ICCP, 2001).

Generally, coal is not composed of only one maceral. The associations of the macerals at a microscopic level are called microlithotypes (Toprak, 1997). In order to seperate the different microlithotypes, the ICCP has agreed that a lithotype can only be recorded if it forms a band > 50 µm, and that lithotypes are not composed purely of macerals from one or two maceral groups, it must contain 5% of accessory macerals (Table 3.5).

It is important to note that high amounts of inertinite, especially fusinite (due to its friability and despite of its high intrinsic hardness) with empty cells and semifusinite in coals promote the formation of very fine dust during mining. Cutting action of the coal is one of the important dust source in mining activities and occurence of the dust formation during this process is directly associated with the petrographical constitution of the coal. McClung et al. (1979) stated that fusain and vitrain formations of coal cause more dust during the cutting action of mining.

Table 3.4 Inertinite macerals according to new updated classification (ICCP,2001)

Macerals with plant cell structures	Macerals lacking plant cellstructures	Fragmented inertinite
Fusinite	Secretinite	Inertodetrinite
Semifusinite	Macrinite	
Funginite	Micrinite	

McCabe (1942) studied the effect of the physical constitution of coal in coal preparation and this research showed that the required amount of power to obtain the specific size of coal by crushing was connected to lithotypes of the coal and it was pointed out that necessary energy to break the fusain into specific size was the smallest one among others and required energy increased in the order as vitrain, clarain and durain.

Table 3.5 Composition of microlithotypes (Larry, 2002)

Groups	Microlithotypes		Composition (Vol. %)
Monomacerals	Vitrite		Vitrinite > 95%
	Liptite		Liptinite > 95%
	Inertite		Inertinite > 95%
Bimacerals	Clarite		Vitrinite + Liptinite > 95 %
	Durite		Liptinite + Inertinite > 95 %
	Vitrinertite		Vitrinite + Inertinite > 95 %
Trimacerals	Trimacerite	Duroclarite	Vitrinite > Liptinite and Inertinite, (each > 5 %)
		Vitrinertoliptite	Liptinite> Vitrinite and Inertinite, (each > 5 %)
		Clarodurite	Inertinite > Vitrinite and Liptinite

3.1.3 Vitrinite Reflectance

Although rank can indicate, in some cases, general processing behavior, it is not sufficient to characterize the specific behavior of a coal under specific utilization conditions. At this point another property of the coal that is called reflectance should be considered to classify the coals. Basically, reflectance can be defined as a measure of percentage of light reflected from a polished surface of coal. This property of coal is directly related with the rank of the coal and it increases with the increasing coal rank (Toprak, 1997).

Coal macerals show some different trends with regard to their reflectance but the reflectance characteristics of vitrinite are considered to change in a fairly uniform manner throughout the coalification series (from low rank coal to high rank coals) and increase with the increasing metamorphism of the coal. Liptinite and inertinite maceral groups exhibit some different reflectance trends. Therefore, the parameters used to classify coals according to rank often reflect the rank of the vitrinite and this remains the most definitive measure of coal rank (Table 3.6 and Figure 3.1).

Another advantage of the Vitrinite Reflectance (VR) over chemical parameters of the coal is that it is not influenced by the relative proportions of the different macerals within the coal (Stach, 1982 in Toprak, 1997). Different types of vitrinite reflectance values can be calculated. Because of the fact that organic materials exhibit anisotropy (in polarized light), by rotating the sample of coal, organic structures will tend to show maximum and minimum reflectance value under linearly polarized light. The most used reflectance values are Rmax values and as previously mentioned earlier, it is used as a coal rank indicator (Toprak, 1997).

Table 3.6 Vitrinite (Huminite) reflectance values (Rmax) (Boggs, 1987, in Toprak, 1997)

Reflectance (Rmax) %	**Paleo-temperature values (^{0}C)**	**Corresponding Coalification Rank**
<0.48	<100	Subbituminous coal
0.59	125	Subbituminous coal
0.72	145	High Volatile Bituminous coal
0.86	165	High Volatile Bituminous coal
1.00	180	High Volatile Bituminous coal
1.16	195	Medium Volatile Bituminous coal
1.42	210	Medium Volatile Bituminous coal
1.50	220	Low Volatile Bituminous coal
1.70	230	Low Volatile Bituminous coal
1.92	235	Low Volatile Bituminous coal
2.14	240	Semi Anthracite

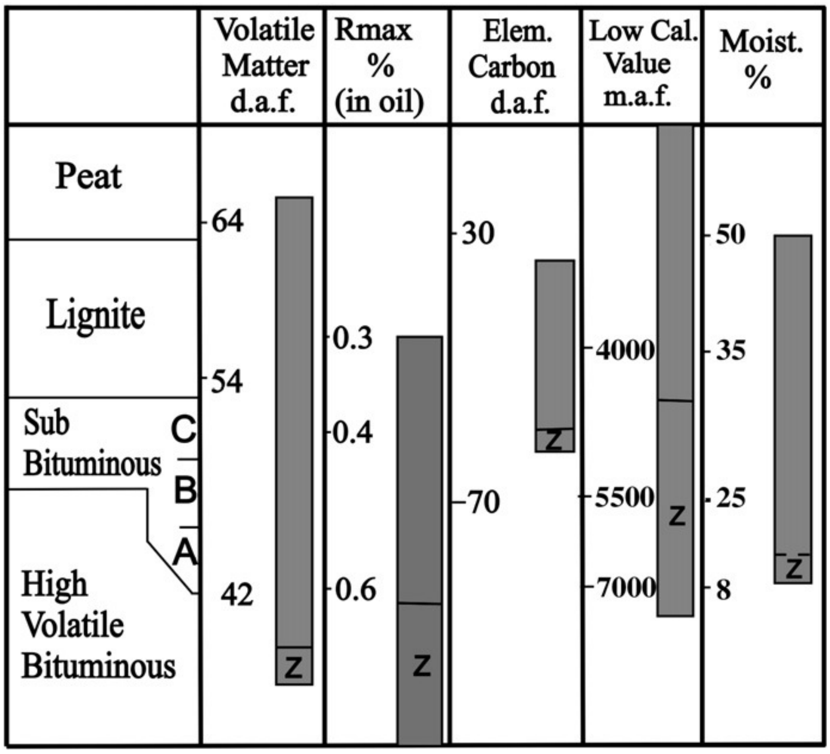

Figure 3.1 Coal rank classification based on ASTM D-388 (Teichmüller and Teichmüller, 1982 in Toprak, 2009)

Generation of the coal dust formation during mining activities is directly correlated with some of the physical and chemical properties of the coal and as it is known that these properties are changed for different coals having different rank. Since vitrinite reflectance is a widely used coal rank indicator, respirable dust generation rate of the coal is also directly related with this property of coal.

Coal is not composed of only organic compounds, at the same time some inorganic materials are also present in the composition of the coal. These are clay minerals (aluminosilicates), carbonate minerals, silica, sulfides and some other minerals. Clay minerals which occur as illite, kaolinite and some other forms and constitutes approximately 50% of the total mineral matter content of coal. The second group is the carbonate minerals and this group is mainly made up of calcite, siderite and dolomite. The third group is the sulfides. Pyrite is the most important substance of this group. Many fossils are mineralized with pyrites, which has evidently been reduced by the action of decomposing organic matter on a solution of ferrous sulphate, or perhaps less directly on ferrouscarbonate dissolved in water containing carbonic acid, in the presence of certain sulphates. A similar action probably explains the origin of pyrites and marcasite in coal. The pyrite (FeS_2) occurs as a discrete particles in a wide variety of shapes and sizes. At the same time, it is distributed in a nonuniform manner throughout the coal (Crickmer, 1981). Silica is another important inorganic substance at the coal and its negative effects on human health in mining industry are explained in previous chapter.

These inorganic materials are also important for human health. For example occurence of the respirable quartz dust in coal causes the development of silicosis, a fatal lung disease. Therefore, organic and inorganic structure of the coal are very important for both coal dust occurence and its negative effects on human health.

3.2 The Effect of Coal Rank on Dust Generation

Rank refers to the classification of coals according to their degree of progressive coalification or maturation. As plant matter decomposes to form coal, different ranks are formed based on increasing temperatures, pressures, and time. These conditions result in chemical and physical changes between ranks of coal, which include fixed carbon, volatile matter, moisture content, heat value, and coking properties. The standard ranks of coal commonly include lignite, sub-bituminous, bituminous, and anthracite, listed in the order of increasing time, temperature, and pressure (Hills, 2007). This maturation steps can also be explained as follows: Coal starts off as peat. After a considerable amount of time, heat, and burial pressure, it is metamorphosed from peat to lignite. Lignite is considered to be "immature" coal at this stage of development because it is still somewhat light in color and it remains soft. As time passes, lignite increases in maturity by becoming darker and harder and is then classified as sub-bituminous coal. As this process of burial and alteration continue, more chemical and physical changes occur and this type of coal is classified as bituminous. At this point, the coal is dark and hard. Anthracite is the last of the classifications, and this terminology is used when the coal has reaches ultimate maturation. Anthracite coal is very hard and shiny (Kentucky Geological Survey Web Page).

Rank of coal also can be defined as the extent to which the organic materials have matured during geological time ongoing from peat to anthracite. In other words, coal rank is the degree of change undergone by coal as it matures from peat to anthracite—a process known as coalification (Hills, 2007).

Some studies have detected that the severity of the coal worker pneumoconiosis is directly related with the coal rank. Attfield and Morring (1992) (in Organiscak and Page, 1998) stated that there is strong evidence that miners who work in regions where high rank coal is mined may be at higher risk of disease; those who work with high volatile bituminous coals are at lower risk.

Most of the studies that have been done to identify the relationship between coal rank and dust generation in laboratory conditions were applied in coal crushing and grinding processes. They indicated strong positive correlation between coal rank and the amount of respirable-sized particles found in the product. During these studies, coal rank were defined by Hardgrove grindability index (HGI), fuel ratio (fixed carbon/volatile matter) and vitrinite reflectance. For example, studies of the Moore et al. (1984) and Baafi et al. (1979) showed that either a grinding or a crushing process produces more fine product and more respirable sized particles in this product for higher rank coals. It is important to state that results of these studies were the measurements of dust in the product and not the measurements of airborne dust.

As Stecklein et al. (1982) pointed out that coal fragmentation from cutting usually occurs, in part, along with planes of imperfections (cleats and joints) or weaknesses containing mineral matter.

Organiscak and Page (2002) concluded that since high rank coals are generally more extensively cleated, cleating is directly related with the respirable-sized particles in the crushed product material for eastern U.S. coals. They explained this situation by the relationship of ash content and at least one mineral constituent (pyrite) to the percentage of airborne respirable dust. In order to confirm this hypothesis, a description is offered which is based on known coal petrography (Figure 3.2).

Schulz (1997) (in Huang et al., 2008) stated that dust of the low-rank coals generates a greater cytotoxicity than dust of high-rank coal. Page et al. (1993) studied on crushing nine bituminous types of coal with a small roll crusher and concluded that lower rank coals produce more airborne dust.

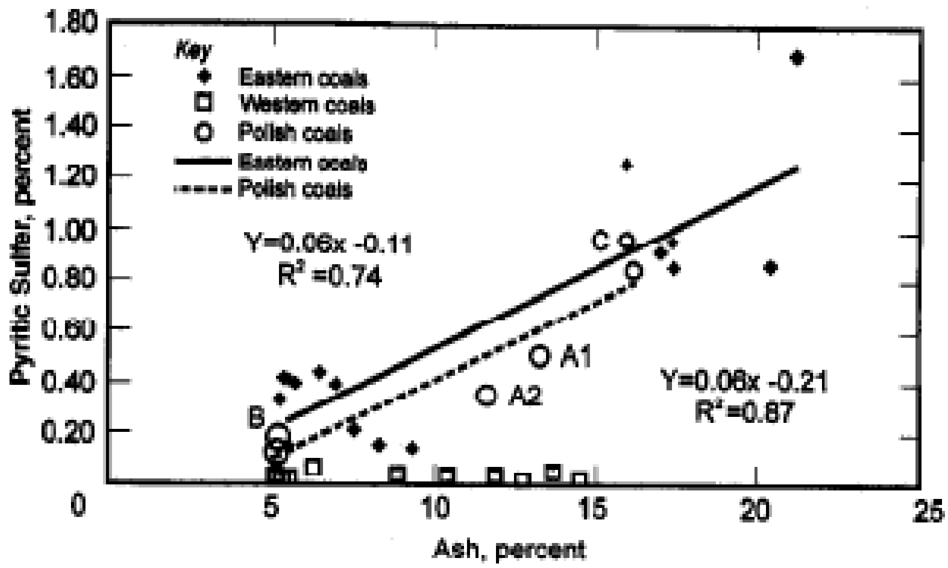

Figure 3.2 Relationship between pyritic sulphur and ash content (Organiscak et al., 2002)

3.3 The Effect of Hardgrove Grindability Index on Dust Generation

Grindability is the physical property of coal which determines the relative ease of pulverizing or grinding a coal. Grindability is a very important factor wherever coal is used in pulverizers, since the capacity, power input and repair costs for these pulverizers vary with grindability index. Grindability is also an important factor for the occurence of the coal dust (Crickmer, 1981).

As stated earlier, coal is composed of both organic and inorganic materials. Grindability of coal is associated with its rank, chemical and petrographical properties. In other words, since all of these properties also affect the coal dust occurence, grindability is also important parameter for dust formation. In order to measure the grindability of the coals, it is essential to use some tests based on size reduction. The Hardgrove Grindability Index (HGI) was developed in the 1930s from experimental work by R. Hardgrove to determine the relative difficulty of reducing various coals to a particle size required for efficient combustion in pulverized coal boiler furnaces. A briefly, this index measures the relative ease of pulverizing a coal in relation to a standart coal for which the grindability is chosen as 100. This index is calculated by using the standart Hardgrove grindability index equipment (Figure 3.3). In order to find the HGI of a coal, the mass of minus 74 µm (200 mesh) fraction of the Hardgrove equipment mill product is used. The HGI is defined as the

$$HGI = 13 + 6.93\,w \qquad (3.1)$$

where, w (gram) is the mass of ground product finer than 74 µm.

Lower Hardgrove grindability index imply a tougher grind, that means greater power consumption and limited output of coal in grinding operations (Hower,1990).

In the work of Organiscak et al.(1992), effect of HGI on airborne respirable coal dust formation were studied. They stated that since HGI is usually expressed as an indicator of coal seam dustiness, it is important to investigate the relation between HGI and respirable coal dust. Results of this study showed that the only strong association found was a significant negative correlation between HGI and tailgate dust concentration ($r = -0.38$, $p = 0.03$), explaining 14 percent of the dust variation. Figure 3.4 shows the scatter plot of HGI versus the tailgate dust concentrations.

Organiscak and Page (1993) studied the relation between HGI and airborne dust concentration with using different comminution processes. They used bituminous coals, applied single and multiple pass breakage process in a closed chamber in order to calculate the amount of generated airborne dust. They found higher correlation between HGI and airborne dust concentration (Figure 3.5) but similar results could not be obtained for the roll crushing process (Figure 3.6). They stated that correlation between these two parametes are closely related with the type of the crushing process and rock content of the coals that are used for experiments. One of the other study conducted by them (1998), they carried out some laboratory crushing experiments by using low to high bituminous coals in order to understand the relationship between some properties of coal and airborne respirable coal dust. In their study, five U.S. bituminous coals were prepared and processed through a double roll crusher located in a low-velocity wind tunnel. They concluded that all of the inherent coal constituents (ash content, fixed carbon content, volatile matter content and etc.) are significantly correlated with HGI.

Baafi (1977) and Moore (1986) conducted some experimental grinding studies among different rank coals and found the Pearson product-moment coefficients (r) between HGI and respirable dust content of coal as (0.97) and (0.91) respectively. Both of them made linear regression analysis between these two variables and their equations explained the 93% and 84% variation of the data respectively and concluded that softer coals produce higher amount of dust than harder coals.

Mitchell (2005) stated that grindability of the low rank coals are difficult than high rank coals. In the work of Trimble and Hower (2002), relationship of the coal petrography and grinding properties were studied and they concluded that coals with high amount of ash and vitrinite maceral can be easily grind than liptinite-rich coals.

Figure 3.3 Standart HGI equipment

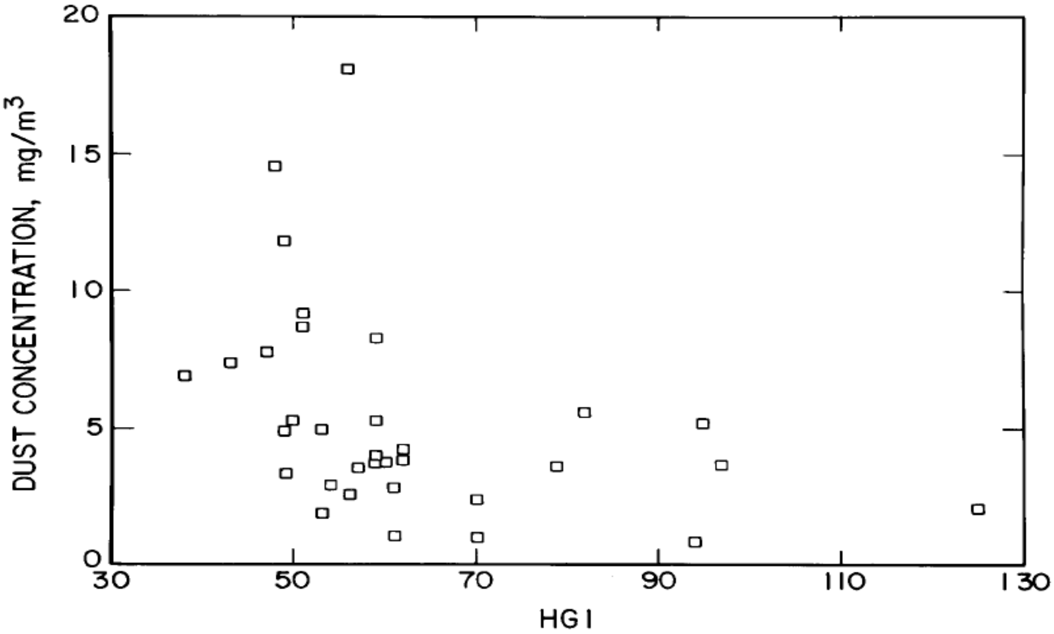

Figure 3.4 Scatter plot of HGI and tailgate dust concentration (Organiscak et al., 1992)

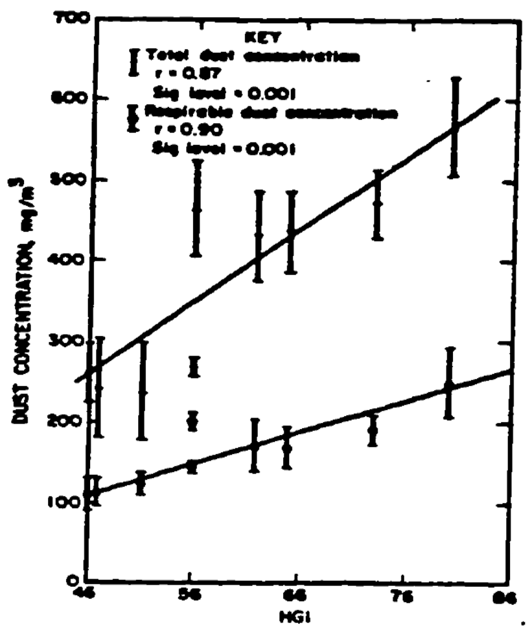

Figure 3.5 Airborne dust concentration versus HGI (multiple pass breakage) (Page et al., 1993)

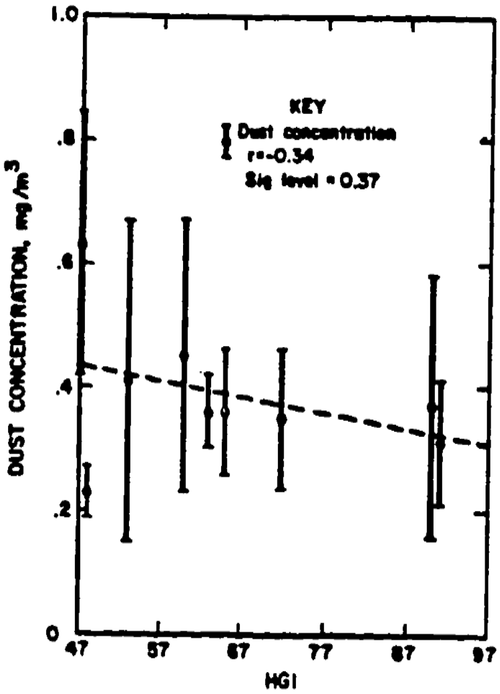

Figure 3.6 Airborne dust concentration versus HGI (single pass breakage) (Page et al., 1993)

3.4 The Effect of Chemical Properties of the Coal

Proximate analysis covers the determination of moisture, volatile matter, fixed carbon, and ash in coals and cokes, and is used to establish the rank of coals. As discussed earlier, rank is an important factor for coal dust generation mechanism and, in other words, these properties of coal are also important in terms of coal dust generation potential.

Proximate analysis method was used as a simple means of determining the distribution of products obtained when the coal sample is heated under specified conditions. The standart test method for this analysis includes the calculation of the three properties and determination of the fourth one from other three values.

Moisture, volatile matter, and ash are all determined by subjecting the coal to prescribed temperature levels for prescribed time intervals. The losses of weight are, by stipulation, due to loss of moisture and at the higher temperature, loss of volatile matter. The residue remaining after ignition at the final temperature is called ash. Fixed carbon is the difference of these three values summed and subtracted from 100 (Speight, 2005).

Moisture is the important constitution of the coal. There are different types of water sources found in coal. During the coal formation process, the vegetation from which coal is formed has a high percentage of water and this water is still present at various stages of the coalification process. But important part of this water is eliminated at the final stage of the coalification process. The total moisture in coal is the determination of the moisture (in all forms except for water of crystallization of the mineral matter) that resides within the coal matrix. In fact, moisture is the most elusive constituent of coal to be measured in the laboratory (Speight, 2005).

Ash is the residue remaining after the combustion of coal under specified conditions and is composed primarily of oxides and sulfates. Mineral matter and ash are different and they should not be confused. Mineral matter is the unchanged part of the coal and ash is formed as a result of the chemical reaction of the mineral matter during ashing process. The potential for the mineral constituents to react with each other can be seen in Table 3.7. Although it was discussed earlier, it is useful to give extra information about the mineral matter content of coal. There are two types of minerals in coal; (1) extraneous mineral matter and (2) inherent mineral matter. Extraneous mineral matter consists of materials such as calcium, magnesium, and ferrous carbonates; pyrite; marcasite; clay; shale; sand; and gypsum. Inherent mineral matter represents the inorganic elements combined with organic components of coal that is originated by the plant materials from which the coal was formed.

Volatile matter, as determined by the standard test methods, is the percentage of volatile products, exclusive of moisture vapor, released during the heating of coal or coke under rigidly controlled conditions.

Fixed carbon is the material remaining after the determination of moisture, volatile matter, and ash. It is, in fact, a measure of the solid combustible material in coal after the expulsion of volatile matter, and like determination of the carbon residue of petroleum and petroleum products.

Thakur (1971) studied on respirable dust generation rate of the coal and developed an index between some properties and respirable dust content of the coal. Respirable dust content of the coal for this index means the part of the sample in the respirable size range.

$$Respirable\ dust\ index = \frac{\left[0.95(FixC)^{0.719}(Fusn)^{0.191}\right]}{(Ash)^{0.168}} \tag{3.2}$$

In this equation FixC, Fusn and Ash are the percentages of fixed carbon, fusain and ash, respectively. But Thakur (1971) stated that this equation was only explained the 35 percent of the variation in the data.

Table 3.7 Behaviour of minerals at high temperatures (Speight, 2005)

Inorganic Species	Behavior on Heating	Consequences for Analysis
Clays	Lose structural OH groups with rearrangements of structure and release of H_2O	Ash weighs less than MM; yield of water increases apparent organic hydrogen, oxygen, and VM
Carbonates	Decompose with loss of CO_2; residual oxides fix some organic and pyritic S as sulfate	Ash weighs less than MM, but this effect partly neutralized by fixation of S as sulfate; CO_2 from carbonates increases apparent VM, organic carbon, and organic oxygen
Quartz	Possible reaction with iron oxides from pyrite and organically held Ca in lignites; otherwise, no reaction	None, unless reactions indicated take place
Pyrite	In air, burns to Fe_2O_3 and SO_2; in VM test, decomposes to FeS	Increases heat of combustion; ash weighs less than MM; S from FeS_2 contributes to VM
Metal oxides	May react with silicates	None (?)
Metal carboxylates (lignites and subbituminous only)	Decompose, carbon in carboxylate may be retained in residue	Uncertainty about significance of ash; most of organic sulfur in coal fixed as sulfate in ash

[a]MM, mineral matter; VM, volatile matter.

Organiscak and Collinet (1999) performed some experiments with using 12 seams and concluded that ash content of the coal is significantly correlated with airborne dust. Page et al.(1993) showed some relationship between rank and airborne dust. They stated that lower rank coals as defined by their moist fuel ratio ((fixed carbon/volatile matter)/inherent moisture content) produced more dust.

Organiscak and Page (2002) performed the laboratory crushing experiments on a range of low to high volatile bituminous coals to understand the parameters influencing airborne respirable dust generation. They stated that relation between ash and dust cannot be established when size of the breaking material is smaller than the cleat size and from this point of view, it is suggested that the ash (mineral matter) responsible for the dust generation is associated somehow with the cleat, fracture, or bedding plane structure of the coals. They also pointed out that the percentage of coal dust particles smaller than 10 μm in the product that are dispersed as airborne respirable dust increases with air dry loss moisture increasing over the range from 1 to 5 % (Figure 3.7).

Organiscak et al. (1992) studied the relationship of coal seam parameters and airborne respirable dust at longwalls, and during this study they investigated 20 longwalls operating in 16 different bituminous coal seams throughout the United States and used correlation matrix to investigate the relationship between most important and independent coal seam properties and airborne dust criteria (Figure 3.8). Pearson product-moment coefficient (r) was used in this matrix to show the relationship between them.

In their study, the dependent variable (dust) was expressed in both concentrations and airborne respirable mass measured per short ton mined during the sampling period (specific dust) at both headgate and tailgate sampling locations. They concluded that high-volatile, low ash coal seams (lower rank bituminous coals) tended to produce more airborne respirable dust (Figure 3.9).

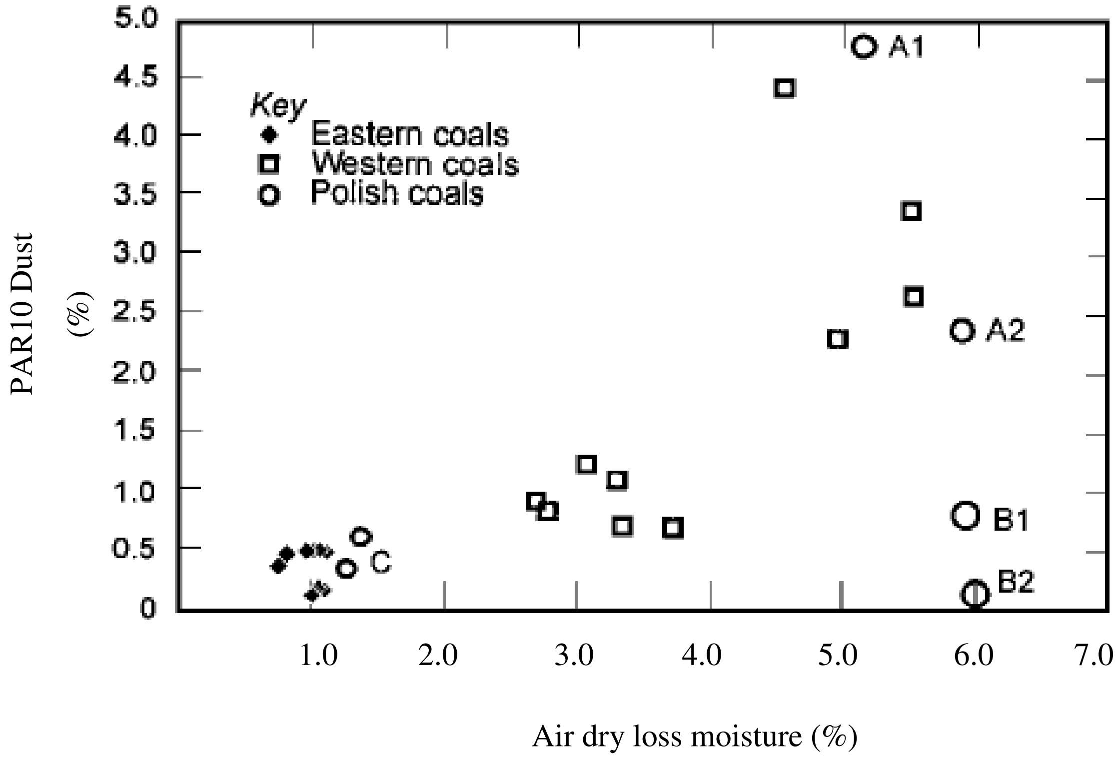

Figure 3.7 PM_{10} versus air dry moisture (Organiscak et al., 2002)

Moisture content	Sulfur content	Ash content	Volatile content	Heat content	HGI	Headgate dust conc	Headgate specific dust	Tailgate dust conc	Tailgate specific dust	
1.000 (33) 0.000	-0.316 (33) 0.074	-0.365 (33) 0.037	0.566 (33) 0.001	-0.175 (33) 0.330	-0.387 (33) 0.026	0.042 (32) 0.818	-0.032 (32) 0.860	0.125 (33) 0.487	0.004 (33) 0.982	Moisture content
	1.000 (33) 0.000	0.796 (33) 0.000	-0.436 (33) 0.011	-0.597 (33) 0.000	0.391 (33) 0.024	-0.226 (32) 0.213	-0.232 (32) 0.202	-0.302 (33) 0.088	-0.234 (33) 0.190	Sulfur content
		1.000 (33) 0.000	-0.531 (33) 0.002	-0.767 (33) 0.000	0.296 (33) 0.944	-0.404 (32) 0.022	-0.427 (32) 0.015	-0.329 (33) 0.061	-0.386 (33) 0.027	Ash content
			1.000 (33) 0.000	0.211 (33) 0.238	-0.857 (33) 0.000	0.199 (32) 0.275	0.051 (32) 0.782	0.405 (33) 0.019	0.201 (33) 0.262	Volatile content
				1.000 (33) 0.000	0.031 (33) 0.865	0.248 (32) 0.171	0.358 (32) 0.044	0.149 (33) 0.408	0.282 (33) 0.113	Heat content
					1.000 (33) 0.000	-0.091 (32) 0.622	0.084 (32) 0.649	-0.383 (33) 0.028	-0.099 (33) 0.583	HGI
						1.000 (32) 0.000	0.909 (32) 0.000	0.483 (32) 0.005	0.631 (32) 0.000	Headgate dust conc
							1.000 (32) 0.000	0.356 (32) 0.046	0.709 (32) 0.000	Headgate specific dust
								1.000 (33) 0.000	0.757 (33) 0.000	Tailgate dust conc
									1.000 (33) 0.000	Tailgate specific dust

KEY
1.000 Correlation coefficient (r)
(33) Sample size
0.000 Significance level (p)

Figure 3.8 Correlation matrix of seam parameters and dust criteria (Organiscak et al., 1992)

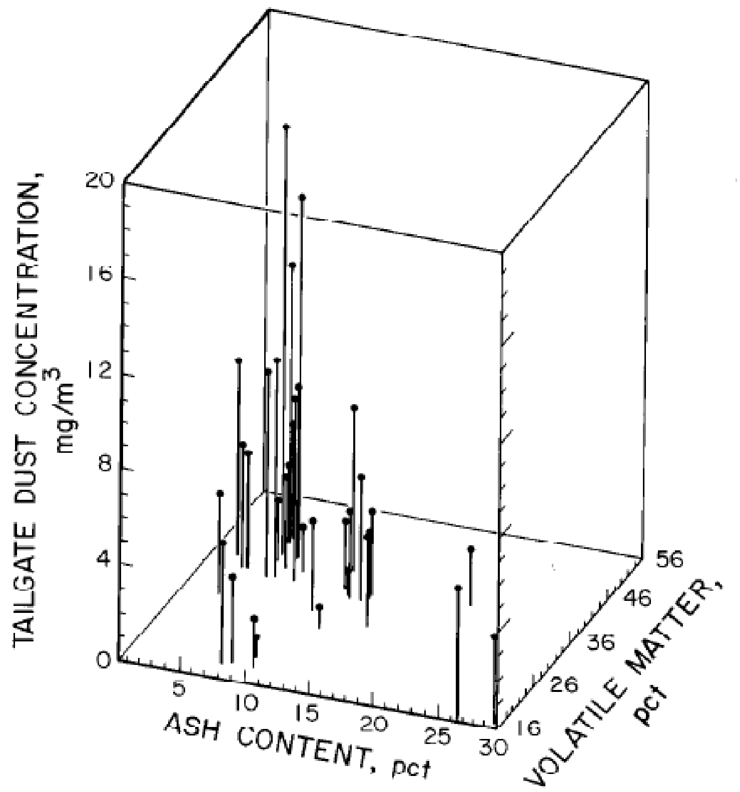

Figure 3.9 Relationship of ash content, volatile matter and tailgate dust concentration (Organiscak et al., 1992)

Organiscak et al. (1992) also stated in their study that scatter plots of individual coal seam parameters and dust (concentration and specific) show that indeed volatility and ash were the parameters with the strongest relationships and these relationships could be accurately characterized as nonlinear in nature (Figure 3.10-3.14). They suggested some nonlinear expression to explain the relation between ash parameter and dust concentration and argued that the ash parameter can better fit several decay models ($y = ae^{-bx}$ and $y = ax^{-b}$) for both specific dust criteria and dust concentrations at both face locations. For example, explanation of the dust variation (R^2) was found 27 percent at the tailgate with the $y = ax^{-b}$ model. However, as a result of their study, they concluded that additional research studies should be done to verify the ash and volatility with airborn respirable dust under strictly controlled conditions by reducing the unexplained data scatter.

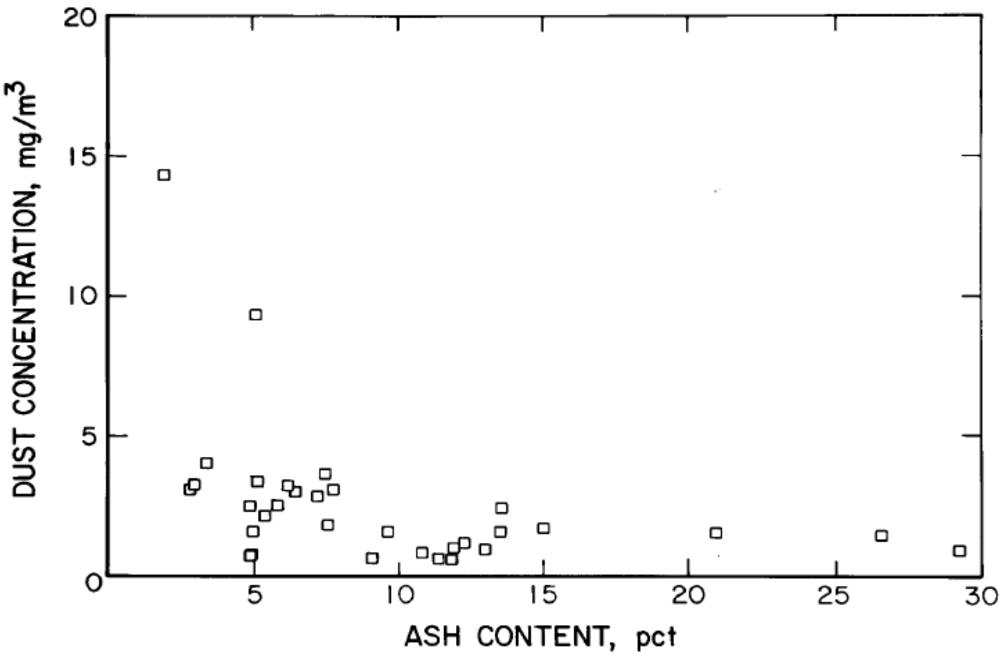

Figure 3.10 Scatter plot of ash and headgate dust concentration (Organiscak et al., 1992)

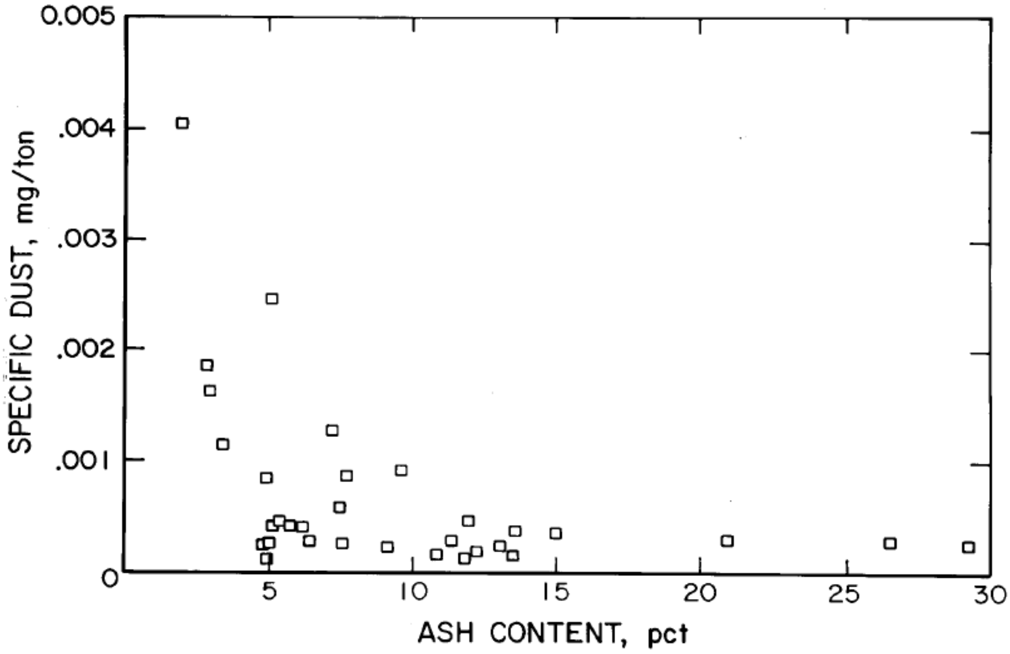

Figure 3.11 Scatter plot of ash and headgate specific (normalized) dust (Organiscak et al., 1992)

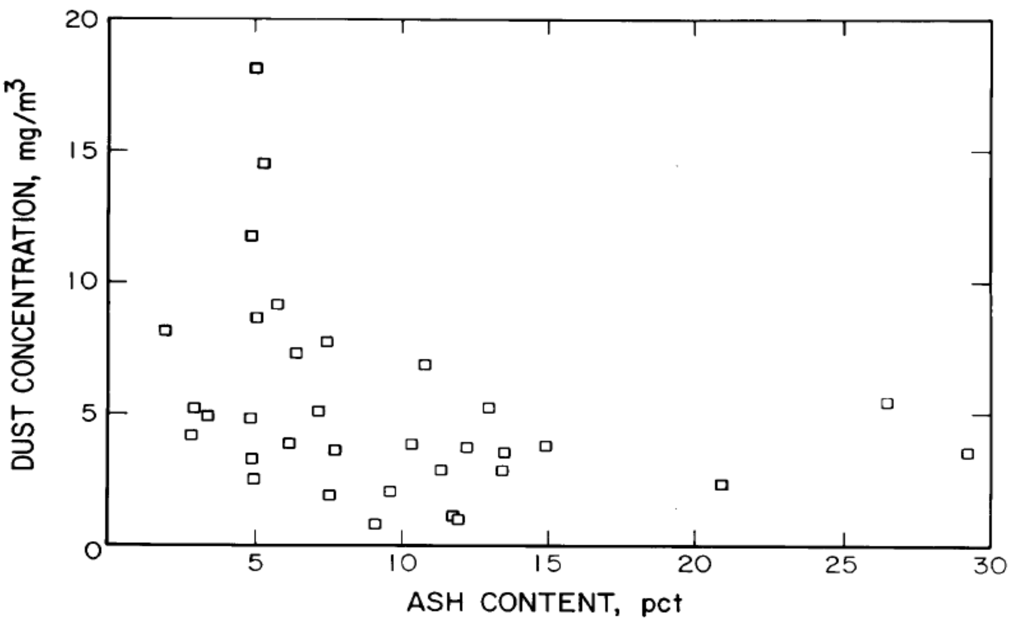

Figure 3.12 Scatter plot of ash and tailgate dust concentration (Organiscak et al., 1992)

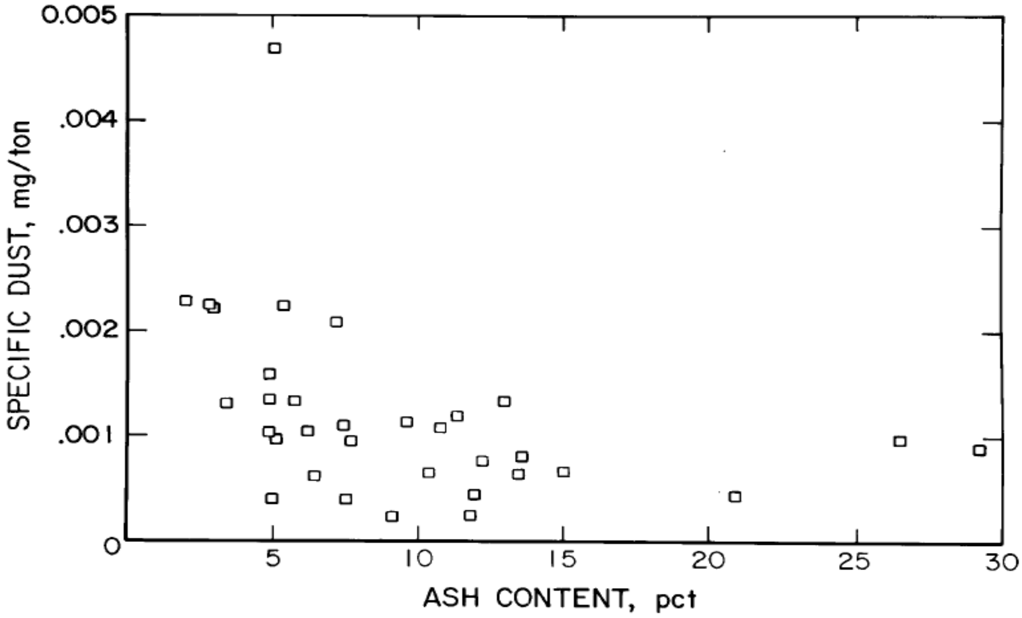

Figure 3.13 Scatter plot of ash and tailgate specific (normalized) dust (Organiscak et al., 1992)

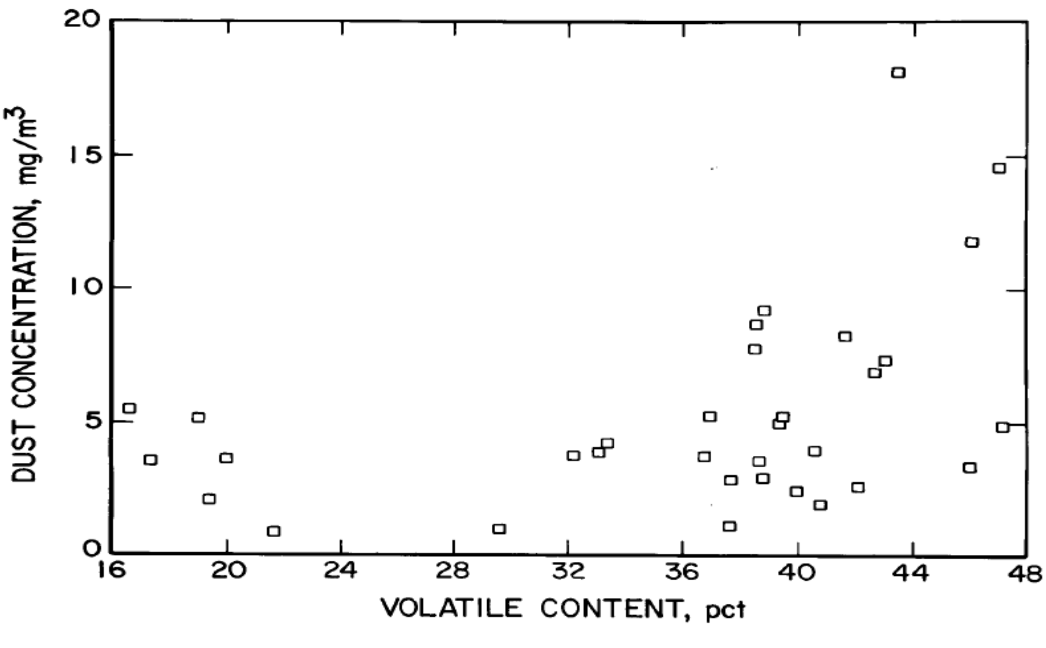

Figure 3.14 Scatter plot of volatile matter and tailgate dust concentration (Organiscak et al., 1992)

Table 3.8 shows the relationship between some of the coal properties and dust concentration (Organiscak and Page, 1998). They stated that insignificant airborne respirable dust correlations were observed for all of the coal constituents and one of them can be seen at Figure 3.15.

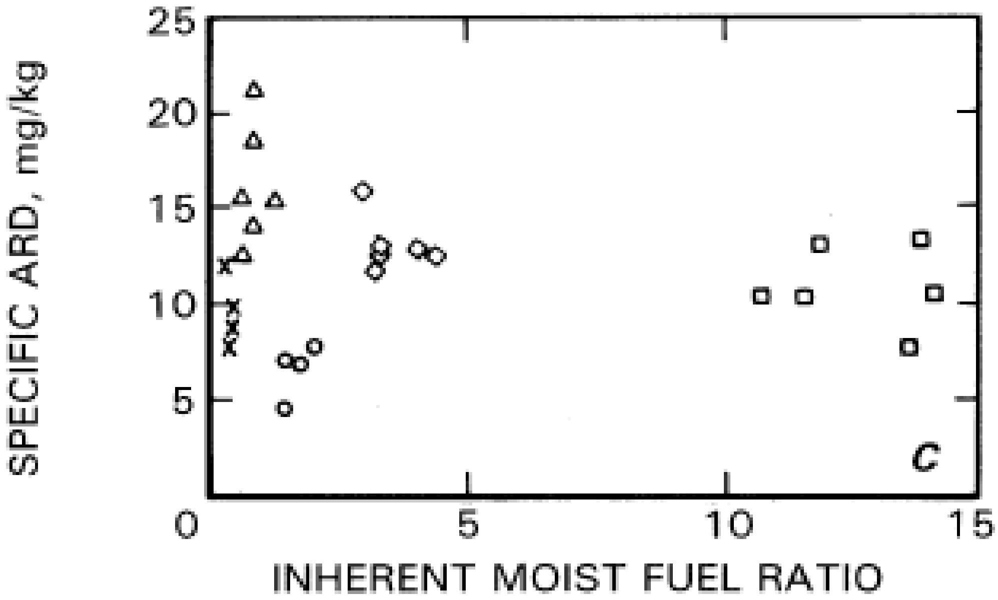

Figure 3.15 Inherent moist fuel ratio versus specific airborne respirable dust (Organiscak and Page, 1998).

As mentioned before, Page at al. (1993) studied the correlation of the proximate analyses with the airborne dust concentration and they conducted single breakage experiments on 10 coal samples at the laboratory conditions. They did not found any relationship between ash and coal dust formation (Figure 3.16). However, negative exponential relationship was detected between moist fuel ratio and airborne dust concentration (Figure 3.17).

Table 3.8 Linear correlations of coal constituents and HGI and specific airborne respirable dust (Organiscak and Page, 1998)

	HGI	Specific airborne respirable dust
Inherent Moisture		
Correlation coefficient	- 0.685	- 0.040
Sample Size	24	26
Significance Level	0.000	0.847
Ash Content		
Correlation coefficient	0.726	- 0.182
Sample Size	24	26
Significance Level	0.000	0.372
Volatile Matter		
Correlation coefficient	- 0.956	0.250
Sample Size	24	26
Significance Level	0.000	0.219
Fixed Carbon		
Correlation coefficient	0.871	- 0.206
Sample Size	24	26
Significance Level	0.000	0.312
Fuel Ratio		
Correlation coefficient	0.988	- 0.175
Sample Size	24	26
Significance Level	0.000	0.392
Inherent Moist Fuel Ratio		
Correlation coefficient	0.986	- 0.134
Sample Size	24	26
Significance Level	0.000	0.514

Baafi (1977) performed some laboratory grinding experiments on sub-bituminous to anthracite coals and used different sizing techniques. Correlations between some of the coal properties and respirable dust content of the coal were investigated.

Respirable dust content of the coal was defined as the cumulative percentage of the Hardgrove mill product finer than 10µm in his study. Experimental studies of Baafi (1977) showed that Pearson product-moment coefficient (r) of moisture, fixed carbon, volatile matter, ash and fuel ratio with respirable dust content of coal were (-0.40), (0.35), (-0.50), (0.23) and (-0.04) respectively.

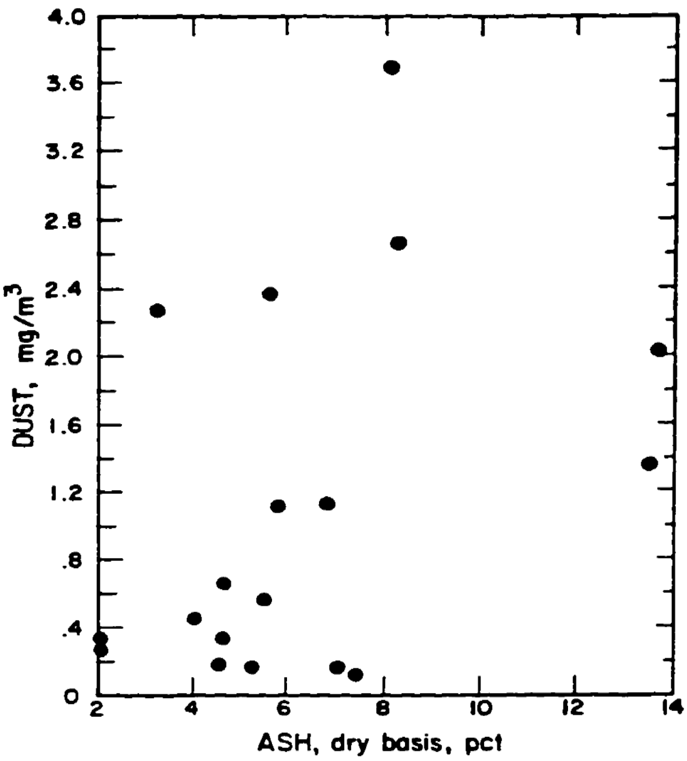

Figure 3.16 Ash content versus airborne respirable dust concentration (Page et al. 1993)

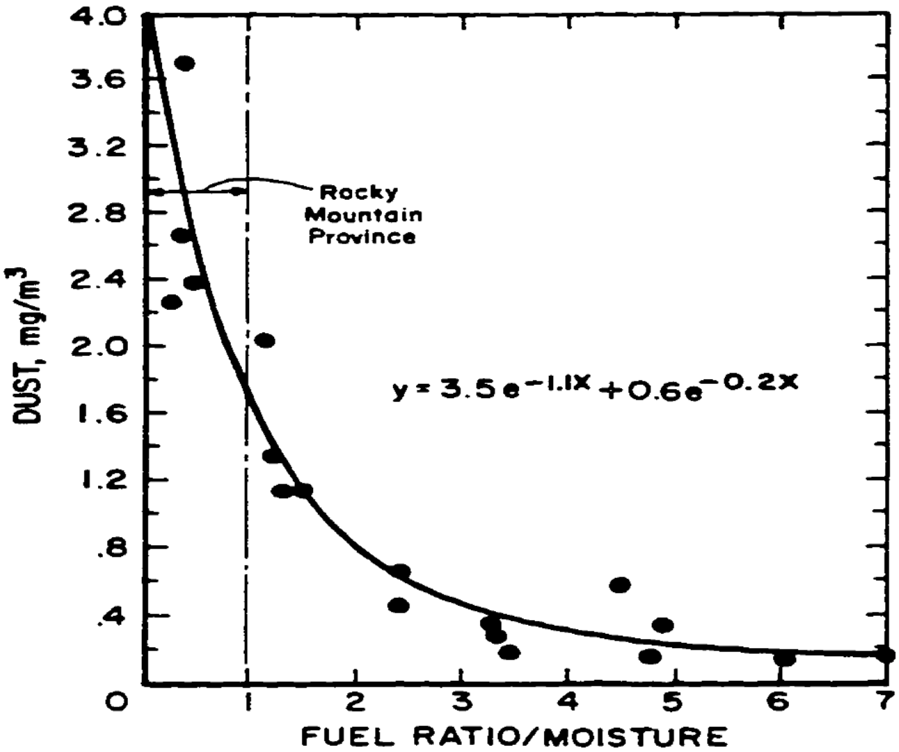

Figure 3.17 Moist fuel ratio versus airborne respirable dust concentration (Page et al. 1993)

Moore (1986) studied on 25 coal samples with different ranks (high volatile bituminous to semi antracite) and like Baafi (1977) he also carried out some grinding experiments and used a microtrac Particle Size Analyzer to understand the size distribution of the -400 mesh fraction. His experimental studies showed that Pearson product-moment coefficient (r) of moisture, fixed carbon, volatile matter, ash and fuel ratio with airborne respirable dust content were (0.06), (0.18), (-0.23), (0.09) and (-0.27) respectively. Moore (1986) also investigated the effects of some petrographic properties of coal on respirable dust generation and applied some statistical analysis on his experimental data (Table 3.9). As can be seen in Table 3.9, only HGI is highly correlated with respirable dust content of coal.

Table 3.9 Pearson product-moment coefficients (r) of some properties of coal with respirable dust content (Moore,1986)

	Respirable Dust Content (%)
Fixed Carbon	
Correlation coefficient	0.18
Significance Level	0.39
Moisture	
Correlation coefficient	0.06
Significance Level	0.76
Ash	
Correlation coefficient	0.09
Significance Level	0.66
Volatile Matter	
Correlation coefficient	- 0.23
Significance Level	0.26
Fuel Ratio	
Correlation coefficient	- 0.27
Significance Level	0.19
Vitrain	
Correlation coefficient	0.05
Significance Level	0.81
Fusain	
Correlation coefficient	0.03
Significance Level	0.87
HGI	
Correlation coefficient	0.91
Significance Level	0.0
Vitrinite Reflectance	
Correlation coefficient	- 0.14
Significance Level	0.51

3.5 Dust Sources in Underground Coal Mines

As the countries started to become industrialized, the need for energy to improve their living standards also began to increase. Today, for most of the countries, coal is still the most important energy source. As stated earlier, by the help of modern mining technologies, production capacities of the coal mining sector started to increase. However the use of modern technology has also brought some of the problems accompanied with it. One of the important problem which should be taken into consideration with a high priority is the generation of the coal dust during mining activities. Niewiadomski and Jankowski (1993) stated that as more coal is mined, more dust is generated. Therefore, the increase in productivity has meant that far more dust is being produced and it must be controlled.

Occurence of the coal dust can be avoided either by preventing the formation of dust during different mining activities, or by suppressing it as near as possible to the source of it. Reduction of dust occurence can also be considered as a part of the dust prevention strategies of coal mining sector. Sometimes it is necessary to apply several effective-dust control techniques at the same time. Ruggieri and Jankowski (1983) suggested some methods to prevent the dust occurence in longwall mining and stated that different dust-control techniques must be utilized in combination, as no single technique can reduce longwall dust concentrations to complience levels, and grouped them as the reduction of dust generated, suppression, dilution, capture or knockdown, extraction and avoidance.

In order to understand the coal dust occurence mechanism, it is very helpful to know the history of how coal has been extracted from past to present. At earlier times, coal was collected by hand from the solid bed by the use of pick and bar. It was then shoveled into baskets, boxes or wheelbarrows and dragged by workers to the outside or to the foot of a shaft. Later, cars were developed but it was still drawn over wood plank by humans. As the time went on, iron straps and then rails were used for transportation of coal.

Mechanization of operations at the face started before 1900 with the development of punching machines and chain type cutters for undermining the coal seam. Rubber-tired shuttle cars were introduced in the 1930s and after 1950s. One of the important development that affected the mining industry was the usage of the tungsten carbide bits in mining industry. Today, these bits are the essential part of the cutting machines and continuous miners. Underground transportation of coal has gone increasingly to a combination of shuttle car to belt conveyor, or shuttle car to belt conveyor to track haulage. After that, fix conveyor systems were introduced and this eliminated the shuttle car. The usage of the longwall mining at coal production was the another milestone for coal mining industry. After 1950s, the German developed the longwall scraper for continuous loading onto a chain conveyor at the face. This was followed by various types of shearing machines developed in several countries (Crickmer,1981) This historical trend of the mechanization of coal mining, at the same time, gives important information related with the coal dust generation. In order to meet the rising demand of energy and coal over the years there has been a trend to increase mechanization in coal mining, with more powerful machines being employed to extract the coal from the working mine face. Jayaramani et al. (1992) conducted a study to identify the sources of respirable dust at high tonnage longwall faces. They found stage loader crusher, coal transport, shearer and support movement as the four main sources of dust generation at longwall mines (Figure 3.18).

Roepke (1984) studied the dust control methods during cutting action and stated that continuous mining generates more dust than conventional mining sytems. They explain the reasons of this situation as due to the fact that conventional mining systems use blasting, explosives causes to break coal into coarse particles. Dust exposures on longwall faces are, in general, significantly higher than in other mining environments. The problem is most severe at operations employing double-drum shearers; many have not been able to consistently comply with the dust standard.

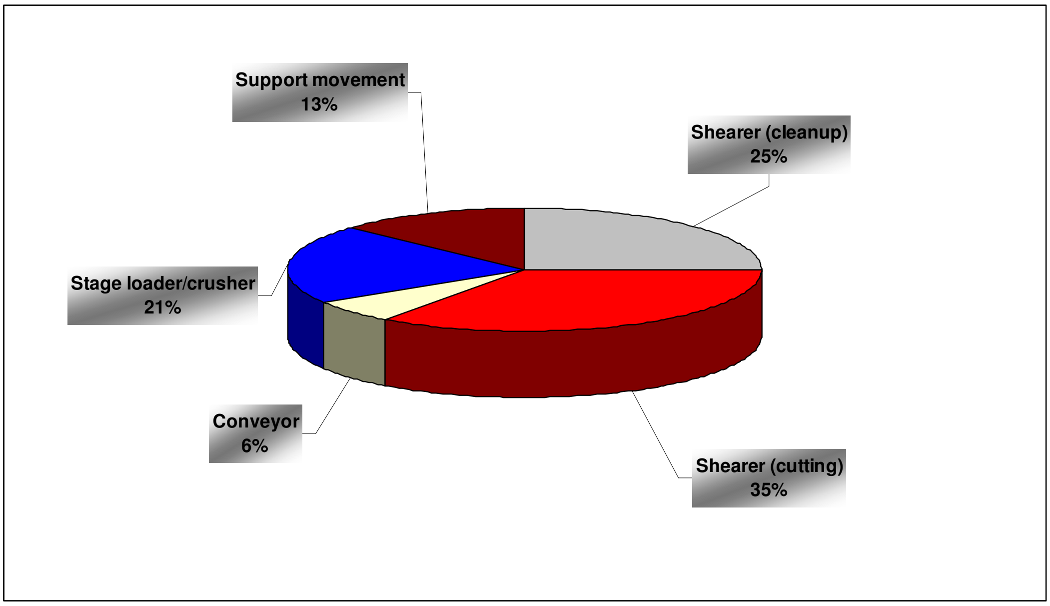

Figure 3.18 Primary dust sources of respirable dust on longwall shearer operations (Jayaramani et al., 1991)

Cutting, drilling, blasting, crushing, loading, transportations are unit operations for different mining methods and at the same time, all of them cause dust generation. Cutting of the coal is the major dust source during coal mining. Jankowski and Organiscak (1983) made a study at six lonwall mines and they identified five primary dust sources: intake dust, dust generated by coal transport and the stage loader, dust generated during movement of the roof supports, dust generated by the shearer during cut pass (primarily a result of the drums' cutting action) and dust generated by the shearer during the cleanup pass (loading of cut material and trimming of bottom rock) (Figure 3.19). Table 3.10 lists the contribution of the each source to the total respirable dust exposures of the longwall shearer operators.

Figure 3.19 Cutting action of the shearer machine (Jankowski and Organiscak, 1983)

As can be seen from the Table 3.10, the most important and major dust source is the cutting action of the shearer. As stated earlier, since cutting action is the principal dust generation source for both continous and conventional mining systems, this study investigated the relationship between the coal properties and dust generation during the cutting action in mines at laboratory conditions.

Table 3.10 Contribution of primary dust sources to overall dust levels

	Percentage of Total Operator Dust Exposure	
Dust Source	Range (%)	Average (%)
Intake	1-9	6
Stageloader-coal transport	13-64	33
Support movement	0-31	12
Shearer		
Head to tail cut pass	0-60	35
Head to tail cleanup pass	15-50	32
Tail to head cut pass	0-47	20
Tail to head cleanup pass	4-20	10

In the early 1980's, the U.S. Bureau of Mines conducted extensive dust measurement surveys at 12 longwall mining with double drum shearers and six of them were regulary in compliance with dust regulation standards, while the other six of them were identified as having the most difficulty in meeting dust regulations standards. The purpose of this study was to identify the operating parameters of both clean and dusty longwalls and to suggest the most effective dust control techniques. Table 3.11 shows that some of the operating parameters of these coal mines. As a result of this study, some factors were identified to contribute to high dust levels on the six operations having the most difficulty in complying with the dust standard. These are the poorly designed external water spray system, marginal water flow to the drums allowing shearer generated dust to become airborne, and minimal controls at the stage loader and crusher, causing immediate contamination of primary intake air. They stated that some precautions should be taken in order to comply with the dust standards. Some of them are: to construct a passive barrier and external water spray system, utilization of large quantities of water particularly through the drum sprays to enhance dust knockdown and prevent dust suspension, effective ventilation and reduced drum speeds (Figure 3.20), (Bumines, 1982).

Table 3.11 Composite of six cleanest and six dustiest longwall operations (Bumines, 1982)

	Six cleanest faces	Six dustiest faces
Cutting Height, (inch)	53-92	66-116
Drum Speed (rpm)	37-45	28-60
Average face air velocity (fpm)	200-315	125-650
Shearer water flow (total), (gpm)	26-85	35-100
Shearer water pressure, (psi)		
External spray system	75-275	0-300
Drum spray system	30-300	15-100
Production (tps)	700-2000	800-1800

Figure 3.20 Shearer drum with water sprays

As it is mentioned above, one of the important aspect related with the dust control is the adjusting the cutting speed. Liu et al. (2009) stated that shearers' dust capacity is directly affected by the design of the shearer.

Deep cutting with slow speed drums decreases the amount of generated dust during cutting action in the mine. Since deep cutting breaks larger coal fragments, amount of coal dust exposed is also reduced. In addition to this, lower drum speed also reduces the fanning action of the cutterheads and thus reduces the amount of dust that becomes airborne (MSHA, 1999).

Reducing drum speed is one of the parameter a longwall operator can make to increase output, reduce respirable dust and decrease machine power consumption (Ludlow and Jankowski, 1984 in Organiscak and Page, 1998). Ludlow and Wilson (1982) (in Karmis, 2001) stated that field tests have confirmed the benefits of slow speed deep cutting and a 60% reduction in dust generation was achieved by reducing the drum speed from 70 to 35 rpm. Today, most of the longwall mining have shearer-clearer system in order to decrease the dust generation during cutting process. The fragmentation process generates most of the respirable dust. Although amount of dust generated during fragmentation mostly depended on the coal properties, cutting parameters and cutting bit configuration are also important. Above-mentioned issues showed that cutting action of the shearer and drum speed are very important in terms of dust generation at coal mining, therefore, in addition to the effect of structural properties of coal dust occurence, this study also examined the relationship between cutting parameters and generation of lignite dust.

CHAPTER 4

EXPERIMENTAL SET-UP

As explained in previous chapters, coal dust formation in mines is very complicated subject. The most suitable and effective dust prevention systems can only be selected by understanding the reasons behind the coal formation. In order to achieve this purpose, one should take different parameters and their relations with coal dust generation at coal mines into account. But, unfortunately, it is very difficult to investigate all of the dust-causing parameters in the same study. In this study, laboratory coal cutting system was developed by using saws with different diameters and during cutting action of the coal, dust concentration of each coal sample was measured. Therefore, relationships between coal dust generation and some of the petrographical, chemical, grinding properties of lignite coal were selected as a baseline of this study.

As mentioned before, cutting process is the most important source of dust in underground lignite coal mines. Therefore, amount of coal dust measured during cutting process was the main concern of this study. The development of a laboratory coal cutting system and determination of the characteristics of the selected coal samples were the major activities of the experimental part of this research.

Since it is the most important domestic energy sources of Turkey and the major part of the active coal mines in Turkey are lignite mines, lignite coal samples were used in the experiments of this study. With regards to this, Bursa, Seyitömer, Tunçbilek, Soma, Beypazarı lignites were selected to be used as a sample of laboratory experiments in this study.

Different types of instruments are available to measure the dust concentration but in this study, real time aerosol dust monitoring equipment was selected. This type of equipment gives information about instantaneous changes of the dust and with the helping of this property, it is easy to detect the main dust sources in mines. As it is known, gravimetric dust samplers are widely used in mines but this type of equipment works during one shift and provides general dust concentration level of the mine. But in order to take the efficient precautions to decrease the amount of dust generation, it is necessary to know the exact sources of dust.

In this study, Microdust Pro real time aerosol monitoring equipment was used in order to determine the amount of coal dust during experiments (Figure 4.1). The Microdust Pro is the portable, real time monitor for assessing concentration of suspended particulate matter. The Microdust Pro measures particulate concentrations using a near forward angle light scattering technique. Infrared light of 880 nm wavelength is projected through the sampling volume where contact with particles causes the light to scatter. The amount of scatter is proportional to the mass concentration and is measured by photo detector. By using a narrow angle scatter (12-20^{o}), the majority of light scatter is in the diffracted and refracted components, which minimizes the uncertainty associated with particle color, shape and refractive index (Anon, 2005).

Figure 4.1 Microdust Pro Probe (Anon, 2005)

The Microdust Pro dust measuring principle can be better explained in Figure 4.2 and Figure 4.3, which show the actual layout of the Microdust pro probe. Under clean air conditions, with the metal slider pulled over the sensing volume, the light comes to rest on the light stop. However, when the metal slider covering the sensing volume is drawn back, introducing the particulate, the beam is scattered around the light stop and onto the photo detector behind it. The amount of scattered light is directly proportional to the particulate concentration.

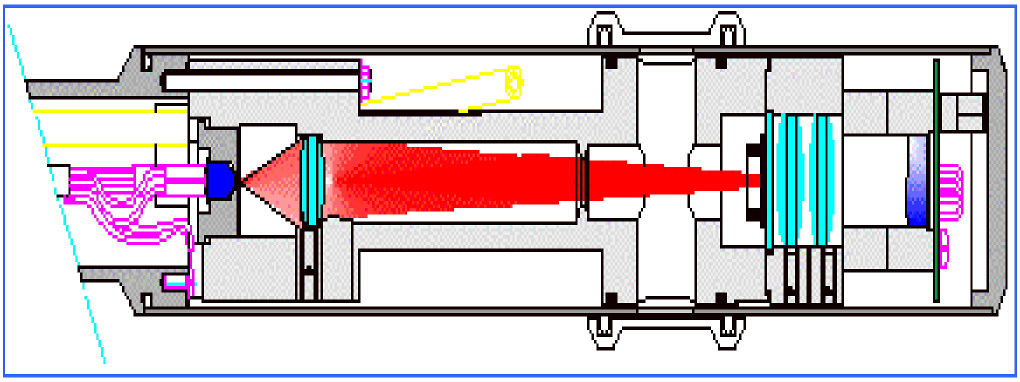

Figure 4.2 Microdust working principle (Anon, 2005)

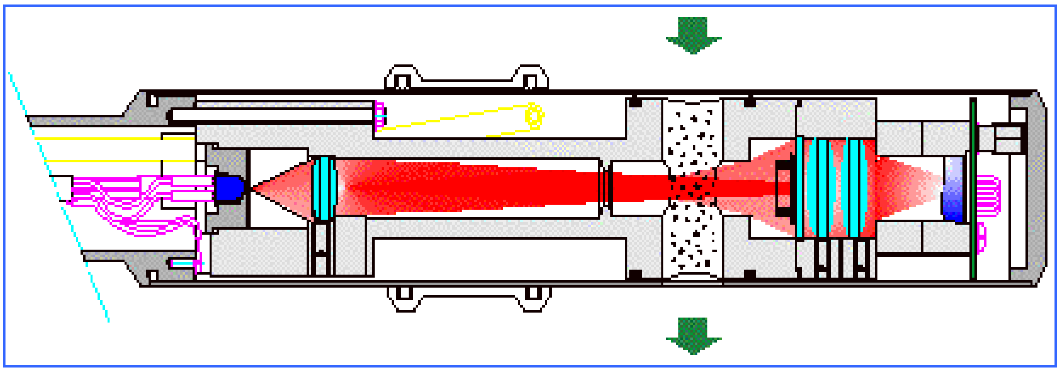

Figure 4.3 Microdust scattering principle (Anon, 2005)

This instrument can measure different range of particle sizes, the smallest being around 0.1 µm to the largest, around 10 µm. This monitoring equipment can measure dust concentration in three different ranges of dust particle size with the helping of the Poly Urethane Foam (PUF) filter adapter (PM_{10}, $PM_{2.5}$ and respirable (5 µm)) (Figure 4.4). These filters are used in the PUF filter head cap during the experiments (Figure 4.5). It is possible to “fix” the range of the instrument, or have it as an “auto-ranging” device. In the study of Baltrenas et al. (2005), as an optical measurement device to obtain the particle concentration, Microdust Pro was used and they stated that one of the main advantages of this device is its capability to measure dust level in a wide range (Anon, 2005).

Figure 4.4 Poly urethane foam filters (Anon, 2005)

At the same time, this instrument provides graphical presentation of concentration trends and internal data logging system to record the dust concentration data during the measurements.

In this study, the WinDust pro Windows TM software package was used to make the downloading and presentation of data as simple as possible .

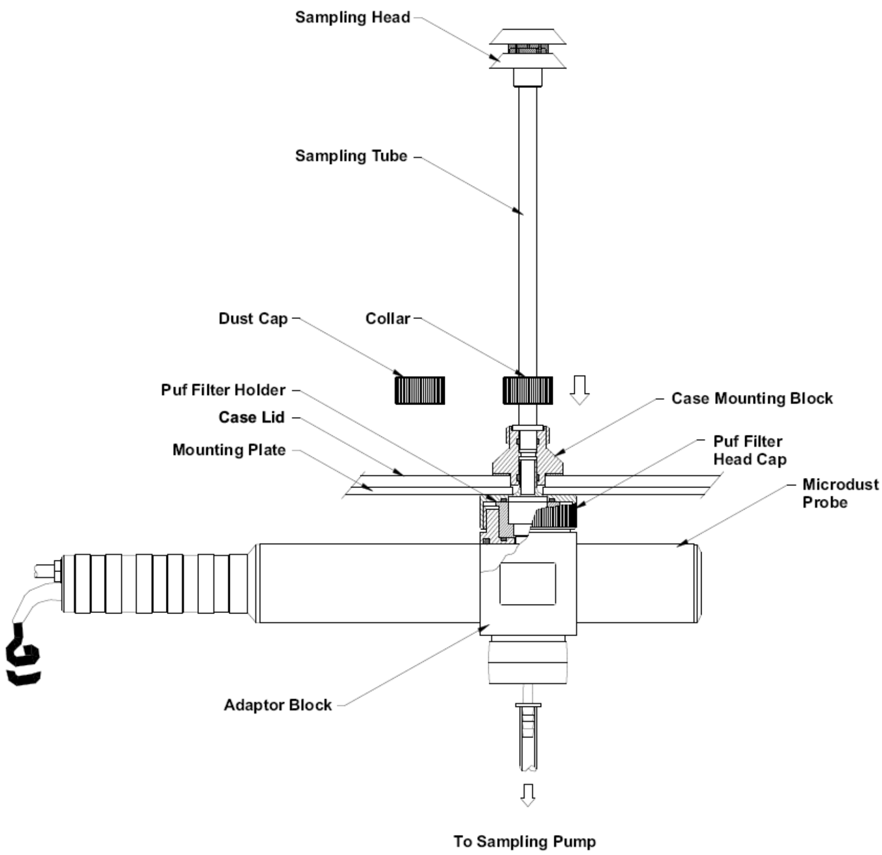

Figure 4.5 Schematic view of the Microdust Pro (Anon, 2005)

The Microdust Pro measures the real-time particulate concentration in mg/m^3 and it is a very versatile instrument available for both fixed site and general survey applications. The genaral layout of the instrument can be seen in Figure 4.6 .

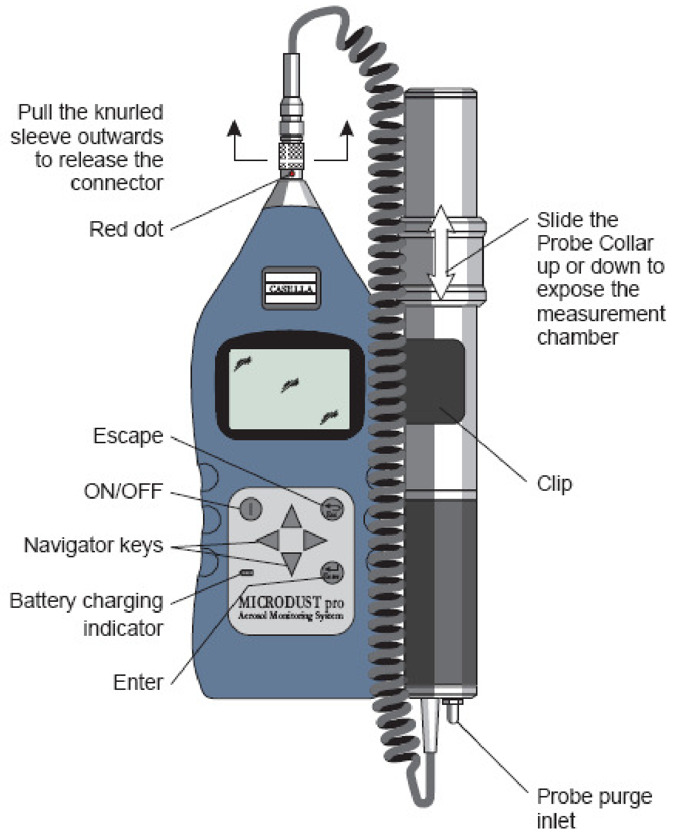

Figure 4.6 The general layout of the Microdust Pro (Anon, 2005)

4.1 Experimental Procedure

In this study, as previously mentioned, lignite samples from Bursa, Soma, Tunçbilek, Seyitömer and Beypazarı (from two different coal seam; upper and lower coal seam) were used to determine the relation between some properties of coal, cutting parameters and amount of dust concentration. During the experiments, block lignite samples were used in order to measure the dust concentrations (Figure 4.7).

Cutting of the lignite samples were conducted at small and large scale saw systems. Large and small scale saw systems can be seen in Figure 4.8 and Figure 4.9 respectively. Major part of the experiments were conducted at the large scale saw system.

Figure 4.7 One of the laboratory coal sample

Figure 4.8 Large scale saw system

Figure 4.9 Small scale saw system

4.1.1 Large Scale Saw System Experiment Procedure

Large scale saw system is composed of a motor and a part where saw attached. This system has the constant rotational speed (1150 rpm). During the experiments at this mechanism, three saws with 40, 50 and 60 cm in diameter were used. For each of the saw, tip speed were calculated according to equation 4.1 seperately, and relationship between dust concentration and this parameter was investigated in detail in Chapter 5.

$$TS = RS \times \pi \times D \tag{4.1}$$

where

TS : Tip speed of the saw (m/min)
RS : Rotational speed of the saw (rpm)
D : Diameter of the saw (m)

Lignite blocks were placed on the table before the cutting process (Figure 4.10). Microdust Pro was placed in a distance of 2 meters from the table of the system. During the cutting process of the lignite samples, this instrument recorded real time dust concentration values in mg/m^3 (range between 0 mg/m^3 to 2500 mg/m^3) for each second of the experiment. System of the Microdust Pro incorporates a sampling pump to draw the sample air through the inlet pipe at selected flow rate. The inlet head is designed to prevent the ingress of insects and other large foreign objects.

Since the degree of the harmful effects of dust particles on human health is directly related with the size of them, this subject was investigated in the laboratory experiments at large scale saw system in this study. As mentioned before, with the help of poly urethane foam filters (PUF), measurement of dust concentration in different dust particle size is possible by using Microdust pro real time aerosol monitoring equipment. The foam filter specifications and dimensions determine the desired aerosol size selection characteristics and eliminate particle sizes greater than desired filter size. The larger particles become trapped and collect within the foam matrix, whilst all particles below these cut-off points pass through the PUF filters and enter the measurement chamber, where the real time mass concentration is established.

As stated earlier, 10 µm is generally considered as the practical upper size limit for penetration in alveolar region and particles having a diameter between 0.5 µm and 5 µm is accepted as a respirable dust range in Turkish regulations. Most of the international studies stated that maximum deposition in the alveolar region occurs at 2 µm and also as mentioned before study of the Park et al. (2008) supported this information.

The above-mentioned issues and most of the studies which examined the relationship between particle size and dust concentration showed that some of the dust particle sizes were considered as the critical values with regard to the human health. Therefore, selection of the dust particle size ranges which were investigated in this study was encountered as a major issue at the beginning of this study. At the selection of the apropriate size selectivity, both real time aerosol monitoring equipment constraints and literature about this subject were taken into consideration and size sampling ability of the Microdust Pro was exactly met the literature requirements. During this study, respirable dust size range was accepted as 0-5 micrometers and dust concentrations were measured at 0-2.5 µm; 0-5 µm and 0-10 µm with using Microdust Pro PUF filters. These filters carefully inserted into their housings in order to obtain accurate measurements during experiments.

Figure 4.10 Table of the large scale saw system

Dust concentrations were measured at different size ranges by using the saws having different diameters (Figure 4.11). Microdust Pro has the internal data logger and records the data during the measurement and after the experiments, these measured dust concentration values transferred from the logger to a computer by using Windust pro application software. This software package supplied with Microdust Pro has been developed to provide the downloading of data as soon as possible. In addition, real time display of the graphical representation of the dust concentration could be seen from the screen of the Microdust Pro by using this software. Both large scale and small scale saw dust concentration measurements were recorded with each one second intervals.

Figure 4.11 General view of the one of the coal cutting saw

4.1.2 Small Scale Saw System Experiment Procedure

Small scale coal cutting mechanism is composed of a moving table and a small scale rotating segment. The table of the mechanism can be moved at nine different velocity. This property of the system is the major advantage of it for this study. Since shearer advancing speed is an important parameter for coal dust formation in underground coal mines, investigation of the effect of these parameter on dust formation at laboratory conditions can be achieved and simulated by using small scale coal cutting mechanism. As previously stated, the large scale saw system can be worked at one constant rotational speed but unlike large one, this system has the ability of working at five different rotational speed.

Different table advancing velocity and rotational speed options of the small scale saw system can be seen at Table 4.1. During the experiments at this system, for each of the nine different table advancing velocities and five different rotational speed of the saw, dust concentration values were measured by real time aerosol monitoring equipment.

Since the rotating segment of this system is small, only one saw with a diameter of 30 cm was used during the experiments. Smaller lignite sample blocks were used and fixed on the table of this experimental set-up (Figure 4.12). Microdust pro was placed in a distance of 2 meters from the cutting action and only upper coal seam lignite samples of the Beypazarı region was used in this experimental mechanism. All of the experiments at the small scale saw system were performed by using only 10 μm PUF filters. That means since this value is accepted as the critical value for dust accumulation and penetration in the alveolar region, only this particle size was examined in this mechanism. The main goal of the experiments that were performed on this set-up was to understand the relationship between dust generation rate and some of the simulated parameters. These parameters are different table advancing velocities, different tip speed of the saw and particle size.

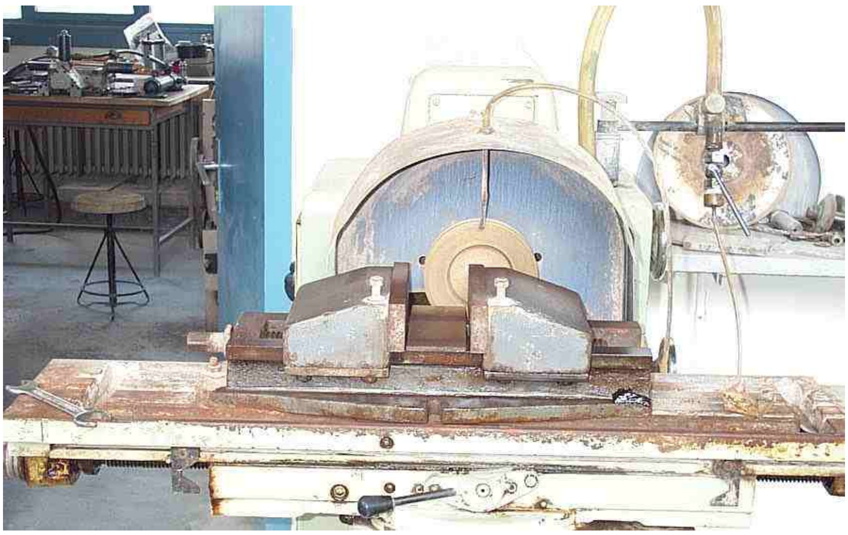

Figure 4.12 Table of the small scale saw mechanism

Table 4.1 Available table advancing velocity and rotational speeds of small scale saw system

Available table advancing velocity (mm/min)	Available rotational speeds (rpm)
11.2	224
16.0	355
22.4	560
31.5	900
45	1400
63	
90	
125	
180	

4.2 Determination of the Coal Characteristics

As stated earlier, the aim of this study is to identify the effects of different parameters on dust generation rate of lignite coal mines. At this point, major factors related with the dust generation was identified with the helping of previous studies associated with this subject. Grindability experiments, petrographical structure analyses, proximate analyses and X-ray diffraction analyses were carried out in order to understand the relationship between these main properties of coal and amount of dust revealing during the cutting process.

The proximate analyses of the experimental lignite samples were carried out in Mineral Processing Laboratory of the Mining Engineering Department of Middle East Technical University and these values can be seen in Chapter 5. Grindability is another important parameter for coal dust occurence. As previously mentioned, one of the accepted methods of grindability measurement is Hardgrove grindability test. In order to perform this test, 50 gram of -14 +28 mesh samples of each lignite specimens were prepared. Then, this amount of samples were put in the grinding bowl of Hardgrove mill. Hardgrove mill consists of a stationary grinding bowl of polished steel balls, each 25.4 mm in diameter. The balls are driven by an upper grinding ring which rotates at 20 rpm and exerts a total pressure of 29 kg and then this mill is rotated 60 times. After grinding, the sample was screened through a 200 mesh sieve, and undersize material was weighted and Hardgrove grindability index values of the coal samples were found by using Eq.(3.1). Hardgrove grindability index values of the coal samples can be seen in Chapter 5.

Coal petrography is another important subject related to the dust generation and all of the petrographical analyses of the lignite coal samples of this study was carried out by General Directorate of Mineral Research and Exploration (MTA) petrography laboratory. All lignite samples were prepared with using special methods in order to study the petrographical structure of them under the microscope (Figure 4.13).

Figure 4.13 Coal petrography Laboratory-Leitz MPV-SP coal microscope

Most of the solid materials can be described as crystalline and when X-rays interact with a crystalline substance, a diffraction pattern can be obtained, and every pure substance have their own characteristics pattern. Therefore, the powder diffraction method is very convenient to characterize and identify the crystalline structure of the substances. As previously mentioned in Section 2.2.2, existence of the crystalline silica in the coal structure causes the development of silicosis, therefore, obtaining the diffraction pattern of the each coal sample is very important issue to gain a knowledge about their potential to generate harmful dust. For this reason, X-ray powder diffraction analyses (XRD) were conducted for all samples. XRD analysis of the lignite samples were performed by General Directorate of Mineral Research and Exploration (MTA) laboratory. XRD analysis results will be discussed in Chapter 5.

4.3 Dust Measurement Analysis Procedure

In order to obtain meaningful results from the measurements, analyses of the results are also important. Relationship between some of the coal seam properties, coal cutting parameters and dust concentration measurements were examined by applying graphical and statistical analysis.

At first, in order to examine the interdependence of the coal and other studied parameters (particle size of dust and tip speed of the saw) and their relations with amount of dust generation, correlation analysis was applied to all of the data obtained from the measurements. Correlation analysis attempts to measure the strength of such relationships between two variables by means of a correlation coefficient (r). The correlation coefficient represents the linear relationship between two variables (Walpole at al.,2002). This means that if the correlation is high, it can be showed by a straight line (sloped upwards or downwards). The correlation (i.e., Pearson product moment correlation coefficient) coefficient (r) is unitless and can always take values between -1 and + 1. If the correlation coefficient is squared, then the resulting value (r^2, the coefficient of determination) will represent the proportion of common variation in the two variables (i.e., the "strength" or "magnitude" of the relationship).

Another value that is used in correlation matrix is the p value. The p-value represents a decreasing index of the reliability of a result. The higher p-value means that the observed relation between variables in the sample is a reliable indicator of the relation between the respective variables in the population. Specifically, the p-value represents the probability of error that is involved in accepting observed result as valid, that is, as "representative of the population." There is no way to avoid arbitrariness in the final decision as to what level of significance will be treated as really "significant." That is, the selection of some level of significance, up to which the results will be rejected as invalid, is arbitrary. In many sciences, results that yield $p \leq .05$ are considered as borderline statistically significant, but it should be remembered that this level of significance still involves a pretty high probability of error (5%). Results that are significant at the $p \leq .01$ level are commonly considered statistically significant, and $p \leq .005$ or $p \leq .001$ levels are often called "highly" significant. However, these classifications represent nothing else but arbitrary conventions that are only informally based on general research experience (Mendenhall et al.,1996).

Secondly, to learn more about the relationship between coal seam properties, particle size of dust, operating parameters (independent variables) and measured dust concentrations (dependent variable), multiple linear regression analysis were used.

This analysis deals with finding the best relationship between y and x, quantifying the strength of that relationship, and the use of methods that allow for prediction of the response values as given values of the regressor x. Simple linear regression can be considered only the case of there is one single regressor variable. The response y is related to the independent variable x through the equation:

$$y = \beta_0 + \beta_1 x + \varepsilon \qquad (4.2)$$

where,

y = dependent variable (variable to be modelled),

x = Independent variable,

$E(y) = \beta_0 + \beta_1 x$ = deterministic component,

ε = random error component,

β_0 = y intercept of the line, i.e., point at which the line intercepts or cuts through the y axis,

β_1 = slope of the line, i.e., amount of increase or decrease in the mean of y for every 1 unit increase in x.

But like this study, in most of the scientific research, there will be more than one regressor that is more than one independent variable that helps to explain y. At this point multiple regression model must be used in order to express the relationship between dust concentration and other coal and cutting parameters. Multiple regression structure might be written as

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + ... + \beta_k x_k + \varepsilon \qquad (4.3)$$

where;
y is the dependent variable,
$x_1, x_2, x_3, ...\ x_k$ are the independent variables
$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + ... + \beta_k x_k$ is the deterministic portion of the model,
β_i determines the contribution of the independent variable x_i.

As stated earlier r^2 is a measure of how well a straight line model fits a data set. In order to measure how well a general linear model fits a data, multiple coefficient of determination that is the multiple regression equivalent of r^2 should be calculated and this term is denoted by the symbol R^2. In other words, this quantity is a measure of the proportion of variability explained by the fitted model. Coefficient of determination takes value between 0 and 1 and the value of it shows that the amount variability explained by the regression equation. For example, if coefficient of determination has the value of 0.5, this means that regression equation has explained the 50 percent of the original variability.

Another important point is the understanding the meaning of the relationship between variables. In order to do this, it should be looked at the signs (plus or minus) of the regression or β coefficients. If a β coefficient is positive, then the relationship of this variable with the dependent variable is positive (directly proportional); if the β coefficient is negative then the relationship is negative (inversely proportional). Of course, if the β coefficient is equal to 0, it means that there is no relationship between the variables.

Another statistical tool that was applied in this study is nonlinear regression modelling. Since the relationship between amount of dust generation and other parameters related with the cutting speed, size of the dust and coal properties are very complex, these relations cannot only be explained by linear model. Therefore, besides multiple linear regression, nonlinear regression was also used in this study to obtain equations that fit the data best.

As stated earlier, Thakur (1971) developed a nonlinear respirable dust index equation (Eq.3.2) but unfortunately, this equation explained only 35 % of the total data. Nonlinear regression is a powerful tool for analyzing scientific data, but since it is a bit complex, some researchers do not want to apply this modelling system into their studies. Nonlinear regression is a general technique to fit a curve through all types of data. It fits data to any equation that defines y as a function of x and one or more parameters. It finds the values of those parameters generating the curve that comes closest to the data. Details of the nonlinear regression models of this study will be explained in Chapter 5.

CHAPTER 5

RESULTS AND DISCUSSION

The dust generated during mining activities constitutes a major threat especially for human health. At this point, understanding the mechanism of dust generation in coal winning can provide a valuable contributions to develop a more effective dust control technologies. Therefore, main objective of this study was defined as to find the relations between dust generation and some of the physical, chemical and petrographical properties of coal seam during mining. Since dust generation is very complex and broad, this research was limited only to cutting process. To conduct the dust concentration measurements, an experiment set was designed in the laboratory conditions. The main underlying reason for selection of cutting process is its major share at the dust generation in underground coal mines. Another reason is that most of the laboratory experiments done in order to investigate the relationship of dust generation and the coal seam parameters during material breakage and drilling processes. Advantages of the laboratory experiments about this subject was explained by Organiscak et. al (1992) and they stated that since too many uncontrolled and unmeasured parameters exist in the underground mining environment, controlled laboratory experiments should be done to determine the most reliable and valid model about coal dust occurence and coal properties.

Lignite block samples brought from six different seams were used during the experiments done in designed laboratory set. In addition, dust particle size for different cutting conditions were also studied to understand how dust particle size is effected by different cutting parameters. At the end, by using properties of coal, dust size and cutting parameters, some of the predictive dust generation equations was developed with regression analysis.

As previously mentioned in Chapter 4, laboratory experiments were conducted by using two systems. These will be named as large and small scale saw experimental sets. Details of the experimental measurements are given in following sections.

5.1 Measurement Results of the Proximate Analysis of the Samples

In proximate analysis, the contents of coal namely, moisture, volatile matter, fixed carbon and ash percents are determined. Results of the proximate analysis of the coal samples are given in Table 5.1.

Table 5.1 Proximate analysis of the lignite samples

Coal Type	**Moisture** (%)	**Volatile matter** (%)	**Fixed Carbon** (%)	**Ash** (%)
Bursa	10,725	53,061	30,216	5,997
Soma	9,043	47,091	39,048	4,818
Seyitömer	13,021	52,115	24,478	10,385
Beypazarı (upper seam)	6,114	41,652	21,679	30,555
Beypazarı (lower seam)	6,621	43,897	4,158	45,323
Tunçbilek	4,850	38,287	50,002	6,860

5.2 Measurement Results of the Hardgrove Grindability Index of the Samples

Hardgrove Grindability Index experiments were conducted in the mineral processing laboratoy of the Mining Engineering Department of METU. Results are given in Table 5.2.

Table 5.2 Hardgrove grindability index values of the samples

Coal Type	HGI
Bursa	28,38
Soma	32,33
Seyitömer	28,73
Beypazarı- (upper seam)	65,46
Beypazarı-(lower seam)	86,25
Tunçbilek	44,60

5.3 Results of the Petrographic Analyses of the Samples

As stated in Chapter 4, petrographic analysis of the lignite samples were carried by the Coal Petrography Department of the General Directorate of Mineral Research and Exploration (MTA) laboratory. Results of the petrographic analysis and maximum vitrinite reflectance of the six lignite samples are given in Table 5.3 and Table 5.4, respectively.

As it has been observed from the results given in Table 5.3, huminite is the most dominant maceral group among all samples and percentage of the this group changes between 54 % to 80 % for all samples. Soma and Beypazarı lower coal seam lignite samples have the highest and lowest percentage of huminite maceral group in their structure, respectively. Highest amount of liptinite macerals observed (% 11) at Seyitömer samples and values of the inertinite macerals of them change from 5 % to 15 %. As can be seen from the Table 5.3, Seyitömer lignite blocks are the most inertinite-rich lignite samples among them. Inorganic constituents of the pyrite content of the lower and upper coal seam of Beypazarı samples are 10 % and 9 %, respectively. They have the highest pyrite content among all samples. In addition, both of them are composed of high amount of clay minerals, quartz and calcite content. Relations between amount of coal dust generation and petrographic and rank properties of coal will be discussed in detail in Section 5.5.4 and 5.5.5.

Table 5.3 Petrographic properties of the lignite samples

SAMPLE NAME	HUMINITE						Total Humin.	LIPTINITE			Total Lipt.	INERTINITE				Total Inert.	PYRITE			Total Pyrite	CLAY AND OTHER SILICATE AND CARBONATE MINERALS
	Tex.	T. ul	E.ul	Dn	At	Gel		Spor	Alg	Ldt		Fz	Mak	Fn	Idt		Pso	Ic	Crc		
BURSA	0	1	4	4	0	65	74	4	2	0	6	1	6	1	1	9	3	0	0	3	8
SOMA	9	12	13	5	0	41	80	3	3	0	6	1	3	0	1	5	2	1	0	3	6
SEYİTÖMER	0	3	5	4	0	53	65	7	4	0	11	2	8	0	5	15	2	0	0	2	7
BEYPAZARI-(UPPER SEAM)	3	4	7	6	0	39	59	3	2	0	5	1	3	0	1	5	6	2	1	9	22
BEYPAZARI-(LOWER SEAM)	2	4	3	4	0	41	54	3	1	0	4	1	4	0	1	6	7	2	1	10	26
TUNÇBİLEK	2	4	7	5	2	50	70	6	2	0	8	2	8	0	1	11	2	1	0	3	8

Tex: Textinite, **T. ul:** Texto ulmenite, **E.ul:** Eu ulmenite, **Dn:** Densinite, **At:** Attrinite, **Gel:** Gelinite, **Spor:** Sportinite, **Alg:** Alginite, **Ldt:** Liptodetrinite, **Fz:** Fuzinite, **Mak:** Makrinite, **Fn:** Funginite, **Idt:** Inertodetrinite, **Pso:** Frammboidal (psodomorf), **Ic:** Idiomorf cristalen, **Crc:** Crack fill

Table 5.4 Maximum vitrinite reflectance values of the lignite samples

Coal Type	**Rmax (%)**
Bursa	0.488
Soma	0.506
Seyitömer	0.519
Beypazarı-upper coal seam	0.444
Beypazarı-lower coal seam	0.449
Tunçbilek	0.523

5.4 X-Ray Diffraction Analyses

X-Ray powder diffraction patterns of the coal samples are given in Figure B.1 to Figure B.6 in Appendix B. Qualitative and quantitative investigation of these patterns showed that clay minerals (especially smectite groups) are the most abundant mineral group for all coal samples. In addition, XRD patterns also exhibited that quartz content of the all samples did not exceed the permissible limit for Turkey (% 5).

5.5 Dust Concentration Measurement Results at Large Scale Saw Mechanism

As mentioned in Section 4.1, 40 cm, 50 cm and 60 cm in diameter saws were used at this experiment group. Rotational speed of this system was constant for each saw size. Tip speed of each saw is given in Table 5.5. For all particle size ranges and tip speeds of saw, cutting process was realized and dust concentrations were measured at every each second by real time aerosol monitoring dust sampler. For all conditions (different tip speed and particle size range) various amounts of experiments were conducted in large and small scale saw system but in calculations, for each specific case, arithmetic averages of them were used as a single value that symbolised the relative case. Average dust concentrations for all experiments at large scale saw system are shown in Table 5.6. Some examples of the experimental results of the each experiment conducted with all samples for all different cutting parameters for large scale saw mechanism are given in Appendix A.

Table 5.5 Tip speed of each saw at large scale saw system

Diameter of Saw (m)	Rotational Speed of the System (rpm)	Tip Speed of Saw (m/minute)
0.4	1150	1445,1
0.5	1150	1806,36
0.6	1150	2167,2

Table 5.6 Average dust concentration of the experiments at large scale saw system

Coal Type	Average dust concentration (mg/m^3)	Particle size (micrometer)(up to)	Tip speed of saw (m/min)
Tunçbilek	5,621	≤ 2.5	1445,1
	7,488	≤ 5.0	1445,1
	9,916	≤ 10.0	1445,1
	5,802	≤ 2.5	1806,36
	13,473	≤ 5.0	1806,36
	19,273	≤ 10.0	1806,36
	11,982	≤ 2.5	2167,2
	19,113	≤ 5.0	2167,2
	21,738	≤ 10.0	2167,2
Soma	4,781	≤ 2.5	1445,1
	9,118	≤ 5.0	1445,1
	13,997	≤ 10.0	1445,1
	5,256	≤ 2.5	1806,36
	10,02	≤ 5.0	1806,36
	15,473	≤ 10.0	1806,36
	9,16	≤ 2.5	2167,2
	11,843	≤ 5.0	2167,2
	15,667	≤ 10.0	2167,2
Seyitömer	8,044	≤ 2.5	1445,1
	9,655	≤ 5.0	1445,1
	12,365	≤ 10.0	1445,1
	9,15	≤ 2.5	1806,36
	12,879	≤ 5.0	1806,36
	14,675	≤ 10.0	1806,36
	11,177	≤ 2.5	2167,2
	18,965	≤ 5.0	2167,2
	49,08	≤10.0	2167,2

Table 5.6 (continued)

Coal Type	Average dust concentration (mg/m^3)	Particle size (micrometer)	Tip speed of saw (m/min)
Bursa	13,644	≤ 2.5	1445,1
	16,561	≤ 5.0	1445,1
	19,637	≤ 10.0	1445,1
	14,285	≤ 2.5	1806,36
	21,719	≤ 5.0	1806,36
	29,982	≤ 10.0	1806,36
	16,235	≤ 2.5	2167,2
	26,31	≤ 5.0	2167,2
	34,406	≤ 10.0	2167,2
Beypazarı Lower Coal Seam	18,003	≤ 2.5	1445,1
	24,93	≤ 5.0	1445,1
	43,299	≤ 10.0	1445,1
	20,685	≤ 2.5	1806,36
	37,065	≤ 5.0	1806,36
	51,57	≤ 10.0	1806,36
	36,419	≤ 2.5	2167,2
	86,104	≤ 5.0	2167,2
	90,109	≤ 10.0	2167,2
Beypazarı Upper Coal Seam	2,851	≤2.5	1445,1
	8,564	≤ 5.0	1445,1
	10,71	≤ 10.0	1445,1
	5,196	≤ 2.5	1806,36
	14,854	≤ 5.0	1806,36
	16,96	≤ 10.0	1806,36
	29,668	≤ 2.5	2167,2
	33,96	≤ 5.0	2167,2
	41,56	≤ 10.0	2167,2

5.5.1 Effect of Tip Speed of the Saw on Dust Formation

The relationship between particle size of dust generated and tip speed of saw is shown in Figure 5.1 to Figure 5.6 for six samples. Figure 5.1 shows this relation for Tunçbilek samples. Amount of dust generated in a range of 0-2.5 micrometers changed slightly (5,621 mg/m^3 to 5,802 mg/m^3) with increasing tip speed of saw from 1445,1 m/min to 1806,36 m/min. But this trend did not continue when tip speed of saw was increased to 2167,2 m/min. Amount of dust generated in this range of particle size was approximately doubled (5,802 mg/m^3 to 11,982 mg/m^3) between 1806,36 m/min and 2167,2 m/min. For the same region, amount of dust generated in 0-5 micrometers particle size range was recorded as 7,488 mg/m^3, 13,473 mg/m^3 and 19,113 mg/m^3 for tip speed of saw of 1445,1 m/min, 1806,36 m/min and 2167,2 m/min, respectively. Amount of dust generated in a range of 0-10 micrometers was measured as 9,916 mg/m^3 at 1445,1 m/min of tip speed of saw for the sample of the Tunçbilek region and for the same sample and particle size range, dust concentration was measured as 19,273 mg/m^3 at 1806,36 m/min. This trend did not continue for the same conditions of 2167,2 m/min and dust concentration was slightly increased between 1806,36 m/min and 2167,2 m/min.

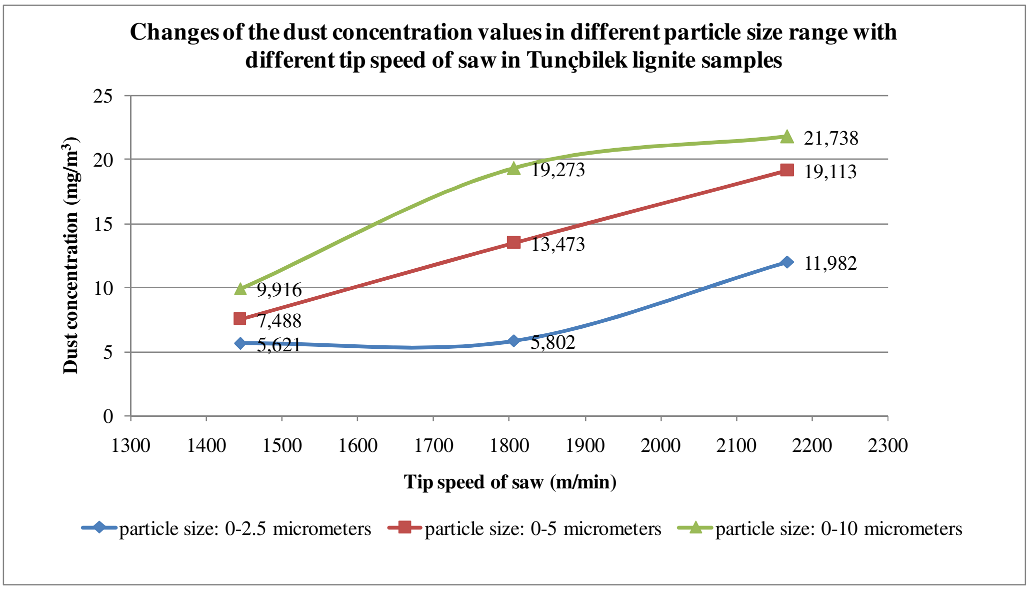

Figure 5.1 Dust concentration values of the Tunçbilek coal samples for different tip speed of saw and particle size ranges

Changes of the dust concentration values of Soma lignite samples for different particle size range and tip speed of saw can be seen in Figure 5.2. For the 0-2.5 micrometers particle size range, dust concentration values were measured as 4.781 mg/m^3, 5,256 mg/m^3 and 9,160 mg/m^3 for tip speed of 1445,1 m/min, 1806,36 m/min and 2167,2 m/min, respectively. For this range of particle size, measured dust concentration values at 1445,1 m/min and 1806,36 m/min were nearly the same. For the 0-5 micrometers particle size range, measured dust values were approximately the same for all different tip speeds of saw. For 0-10 micrometers size range, dust concentration values were measured as 13,997 mg/m^3 at 1445,1 m/min. For 1806,36 m/min and 2167,2 m/min of tip speed of saws, dust concentration values were measured as 15,473 and 15,667 mg/m^3, respectively. This means that for 0-5 micrometers and 0-10 micrometers particle size ranges of Soma samples, effect of the tip speed of saw on dust concentration values are very small.

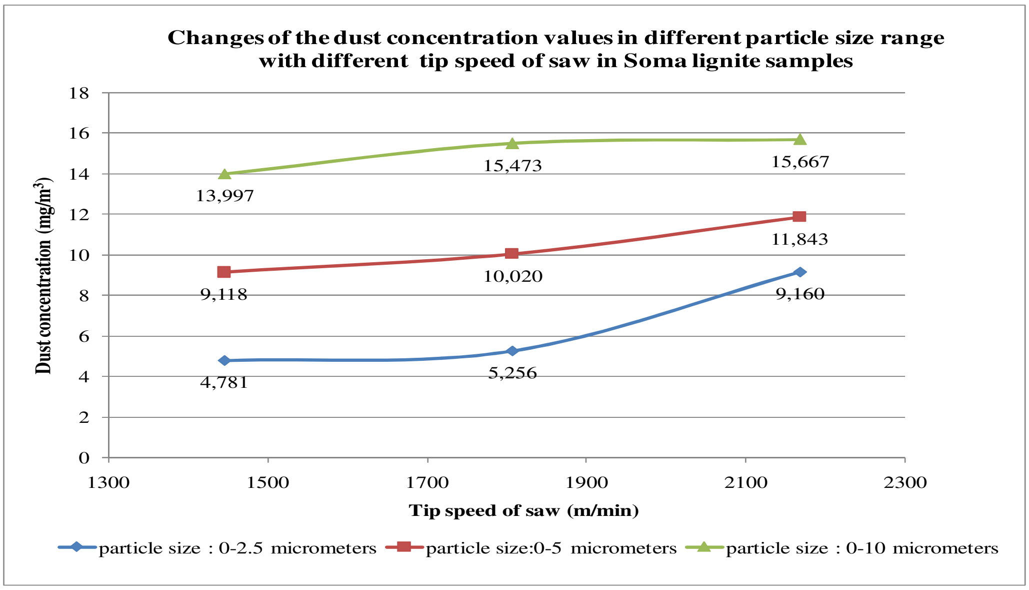

Figure 5.2 Dust concentration values of the Soma coal samples for different tip speed of saw and particle size ranges

Similarly, for Seyitömer coal samples, differences of dust concentration values at 0-2.5 micrometers particle size range were very small for each of the tip speed of saw. Dust concentration values increased from 12,879 mg/m^3 to 18,965 mg/m^3 (for 1806,36 m/min and 2167,2 m/min respectively) for 0-5 micrometers. For 0-10 micrometers dust particle size range, dust concentration values are close to each other at 1445,1 m/min and 1806,36 m/min but it reaches a value of 49,080 mg/m^3 at 2167,2 m/min that is approximately three times higher of the value of the dust concentration of 1806,36 m/min (Figure 5.3).

As shown in Figure 5.4, for 0-2.5 micrometers particle size range, measured dust concentration values are very close to each other for three different tip speeds of saw, but for other particle size range intervals (0-5 micrometers and 0-10 micrometers), dust concentration values increased with the increasing tip speed of saw for Bursa lignite samples.

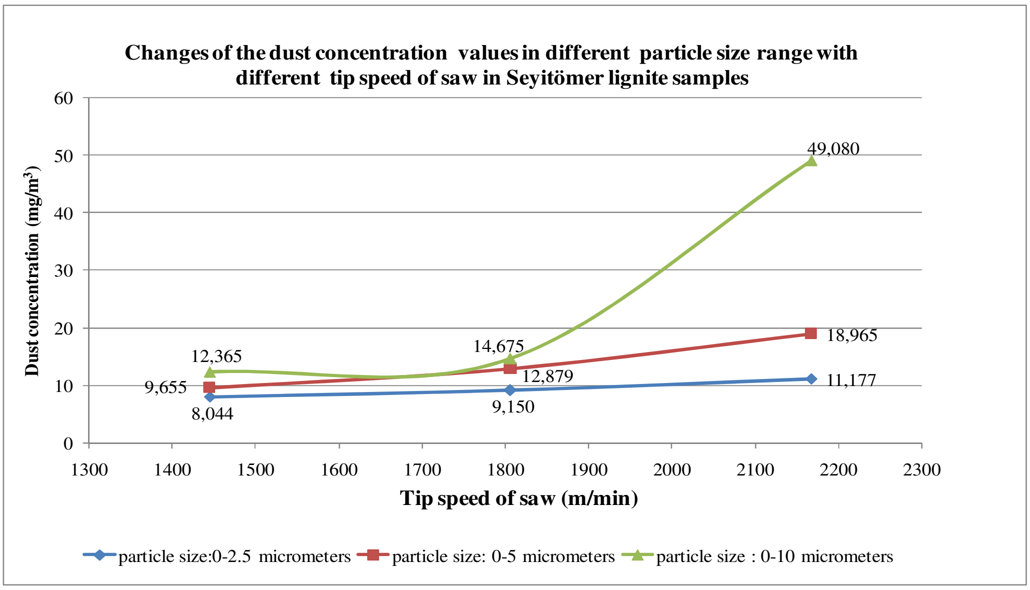

Figure 5.3 Dust concentration values of the Seyitömer coal samples for different tip speed of saw and particle size ranges

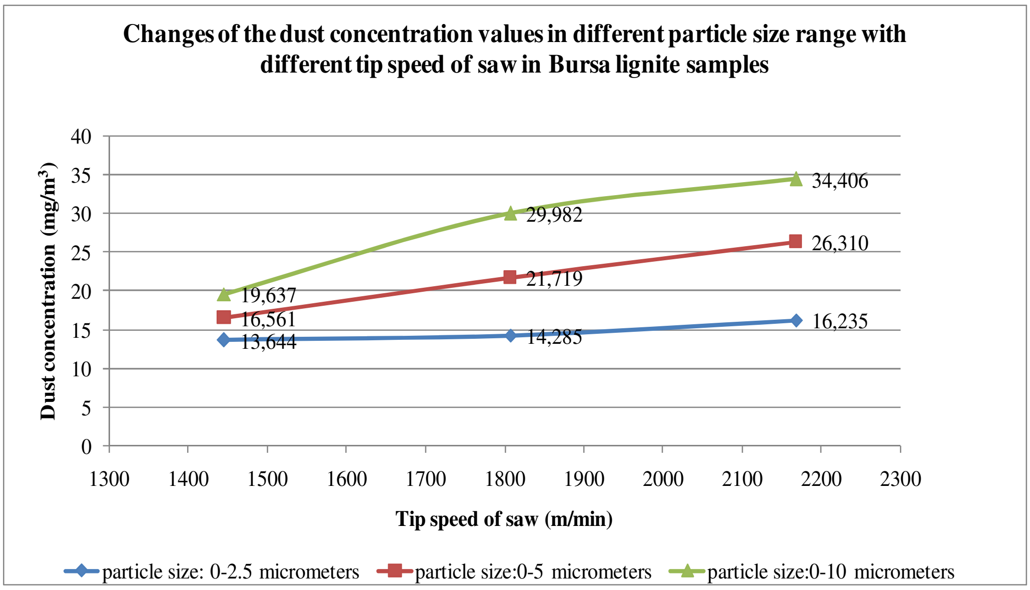

Figure 5.4 Dust concentration values of the Bursa coal samples for different tip speed of saw and particle size ranges

Dust concentration measurements of the lower coal seam of the Beypazarı lignite samples showed that high amount of dust generated at 2167,2 m/min for all particle size ranges and values of the dust concentration at 0-10 micrometers nearly as twice much as of the 0-5 micrometers (Figure 5.5). Similar trend in dust concentration values can also be seen for upper coal seam of the Beypazarı lignite samples measurements except 0-2.5 micrometers particle dust size range. As shown in Figure 5.6, at this particle size range, dust concentration values increased from 5,196 mg/m^3 (at 1806.36 m/min) to 29,668 mg/m^3 (at 2167,2 m/min) which is six times more as fold differences between two of them.

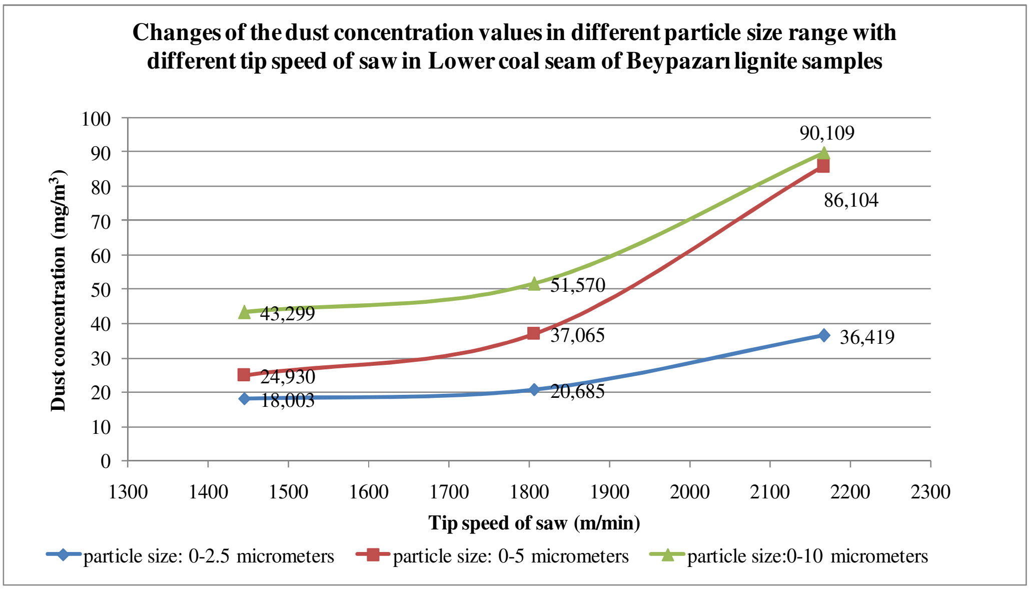

Figure 5.5 Dust concentration values of the lower coal seam of Beypazarı samples for different tip speed of saw and particle size ranges

If dust concentration values of the different samples are considered as a whole, which means that taking the arithmetic averages of the dust concentrations for each sample in the same particle size and tip speed of saw, these values may give the valuable information about relation between dust concentration, particle size and tip speed of saw. As shown in Figure 5.7, for all particle size ranges, dust concentration increased with rising tip speed of saw. For 0-2.5 micrometers particle size range, very small increasing in dust concentration was detected when tip speed of saw increased from 1445,1 m/min to 1806,36 m/min. However, significant increase in dust concentration was measured for this particle size range when tip speed of saw was 2167,2 m/min. For respirable particle size range (0-5 micrometers) dust concentrations increased with increasing tip speed of saw. For 0-10 micrometers particle size range, again dust concentration values increased with rising tip speed of saw but amount of increasing in dust concentration was higher when tip speed of saw was 2167,2 m/min. Almost all coal samples shows similar trend when tip speed changes. This means that amount of increase in dust concentration is not very significant when cutting tip speed of the saw is increased from 1445,1 m/min to 1806,36 m/min. But when tip speed of saw increases to 2167,2 m/min, dust concentration increases significantly.

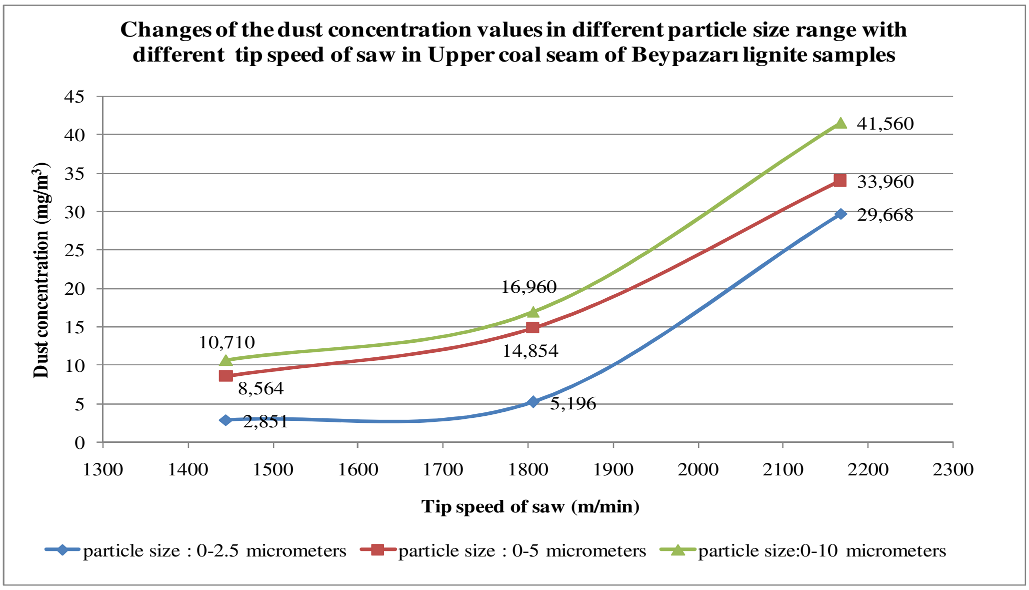

Figure 5.6 Dust concentration values of the upper coal seam of Beypazarı samples for different tip speed of saw and particle size ranges

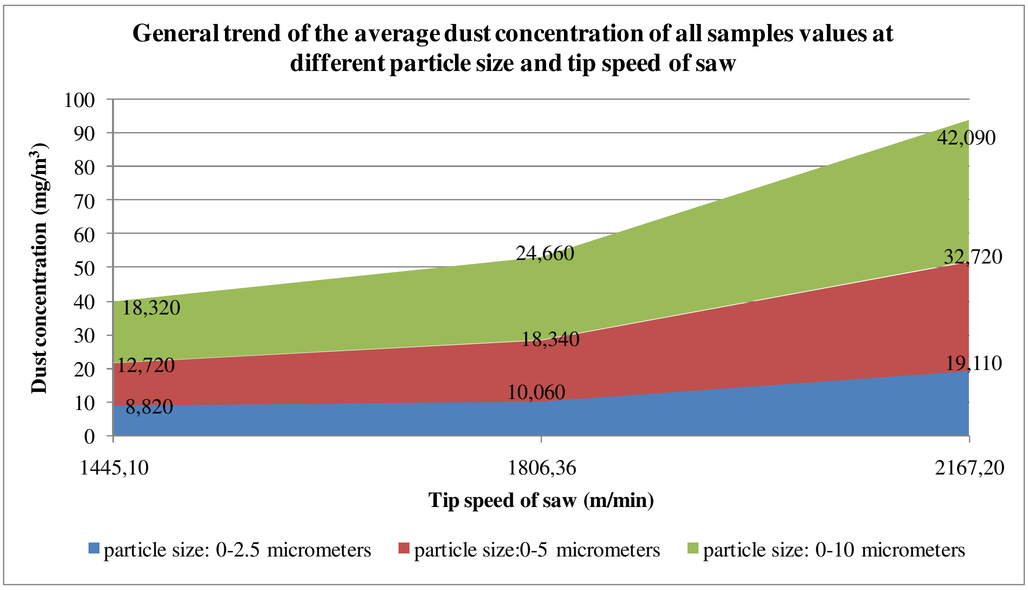

Figure 5.7 General trend of the average dust concentration of all samples values at different particle size and tip speed of saw

5.5.2 Effect of Hardgrove Grindability Index on Dust Formation

Hardgrove grindability index values of all samples were given at Table 5.2. In order to understand the relationships between these values and dust concentration of all samples, some scatter plots of the HGI versus dust concentrations for all size range and tip speed of saws can be seen from Figure 5.8 through Figure 5.10. As can be seen from these figures, dust concentration values measured at different cases decrease in the range of 28,38 and 32,33 of HGI interval.

Although dust concentrations of the samples having an HGI value in the range of 32,33 and 65,46 do not indicate a significant trend, it is important to notice that measured concentrations in that range of HGI values for all particle size intervals at 1445,1 m/min and 1806,36 m/min of tip speed of saw are very close to each other within themselves but some fluctuations are seen at 2167,2 m/min of tip speed of saw. As stated earlier, theoretically, dust concentration values rise with further increase in HGI, although some deviations were seen especially in samples having a HGI values in the range of 28,38 and 32,33, Figures 5.8 to 5.10 shows that amount of generated dust during the experiments generally increases with further rise in HGI especially for the tip speed of 2167,2 m/min. These fluctuations are consistent with explanations of the Hseih (1976) about the variability of HGI for coals having the same rank. According to him, this diversity is caused by differences in mineral and maceral content of the coal samples. In general, it can be concluded that as the HGI gets higher than 50, there is a quite increase in the production of respirable dust.

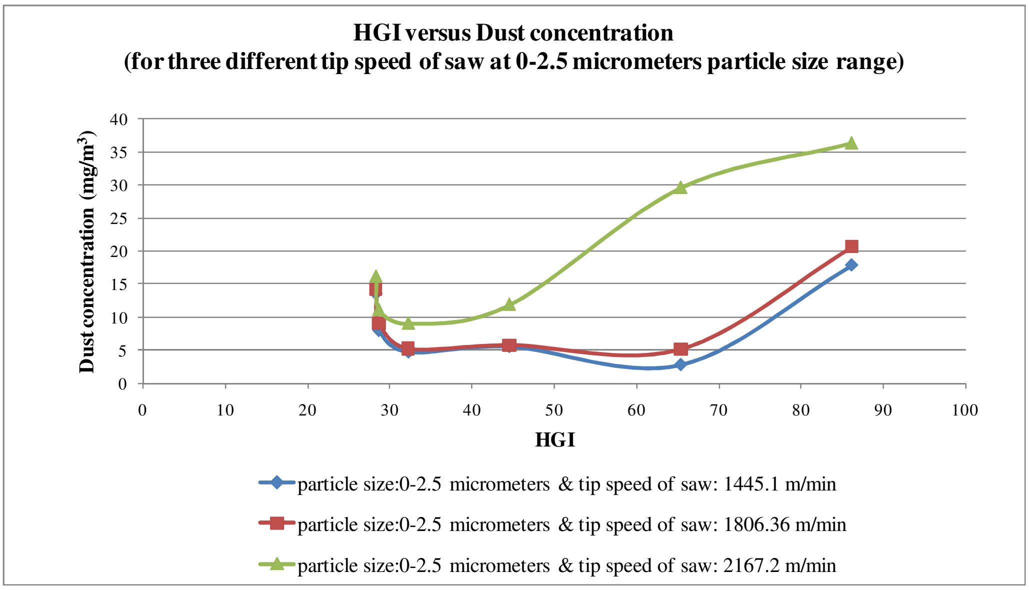

Figure 5.8 HGI versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

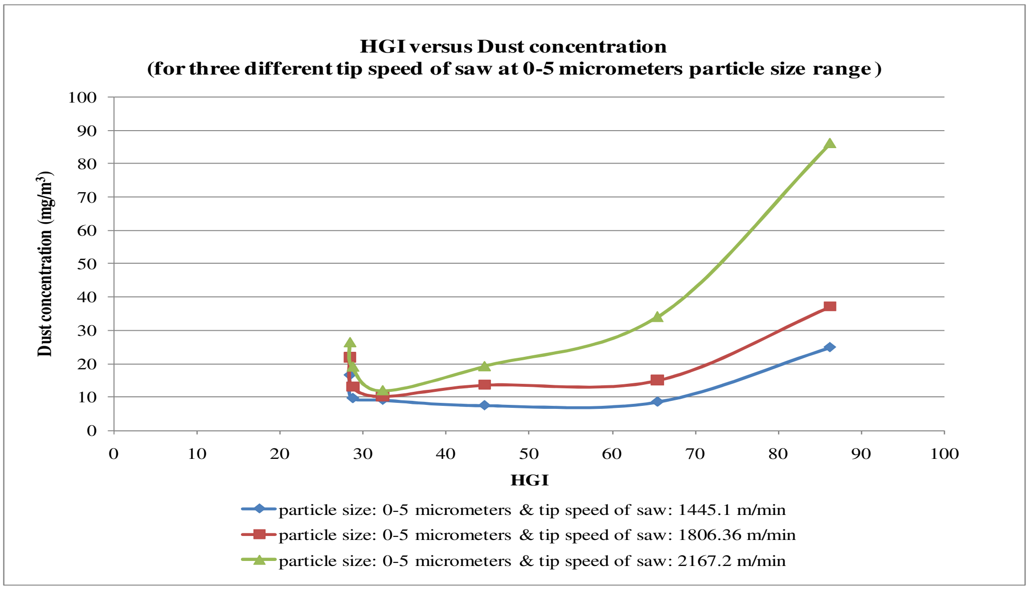

Figure 5.9 HGI versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

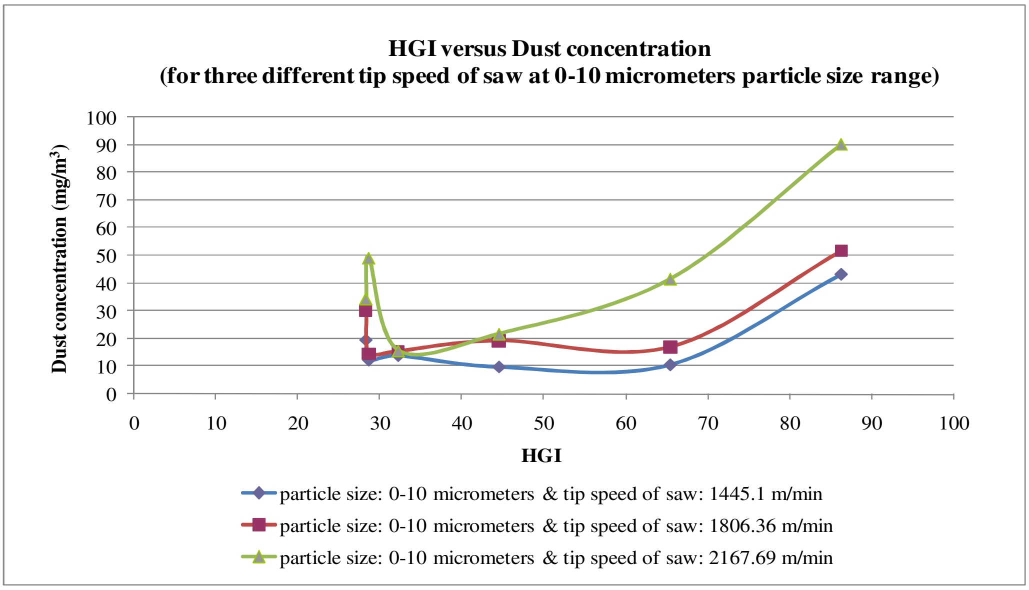

Figure 5.10 HGI versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

5.5.3 The Relationship Between Some Chemical Properties of Coal and Dust Concentration

Proximate analysis is very important in order to characterize the coal samples. By the help of this analysis, components of the coal samples used in the experiments were determined and effect of these properties on amount of dust generation rates were investigated. Ash content of coal is an important parameter in terms of the dust generation potential of them. Graphical representation of the dust concentrations versus ash content of the coal samples at different tip speeds of saw are shown in Figure 5.11 through Figure 5.13.

As can be seen from these plots, for all particle size intervals, although there are some exceptions, dust concentration values are very close to each other at

1445 m/min and 1806 m/min tip speed of saw for all ash content of the lignite samples. When the ash content of samples have a value in the range of 4,818 to 10,385 percent, dust concentrations show some fluctuations. This trend appears to be followed by a rapid increase for all cases in the range of ash content between 30,555 to 45,323 percent. This increasing trend is starting with a value of 10,385 percent ash for the respirable size range of dust (0-5 micrometers) particles. In addition to these remarks, in generally, as far as the ash content of the coal samples is considered, it has been observed that coal having an ash content higher than 10% has quite good positive correlation with this property. This means that higher ash content of the coal causes the generation of higher dust.

Effect of the volatility on dust generation is another important point that should be taken into consideration. Figures from 5.14 to Figure 5.16 show the association of this parameter with measured dust concentrations. For all particle size intervals and tip speeds of saw, dust concentrations reach the peak value when the volatile matter content of the coal is approximately 43 percent and this result is consistent with the study of the Organiscak et al. (1992) and they argued that the ash and dust concentration relationship at the tailgate was roughly opposite of the relationship of the volatile matter and dust concentration. After peak point had been reached then the dust concentrations decreased sharply in the range of volatile matter content from 43,897 to 47,091 percent for all cases. Although some minor trends were detected between dust concentration and volatile matter content of the coal, this is not enough to conclude a general remark about this relationship. Therefore, it could not be obtained any significant relationship between volatile matter content and the amount of respirable dust generated during the cutting process in this study.

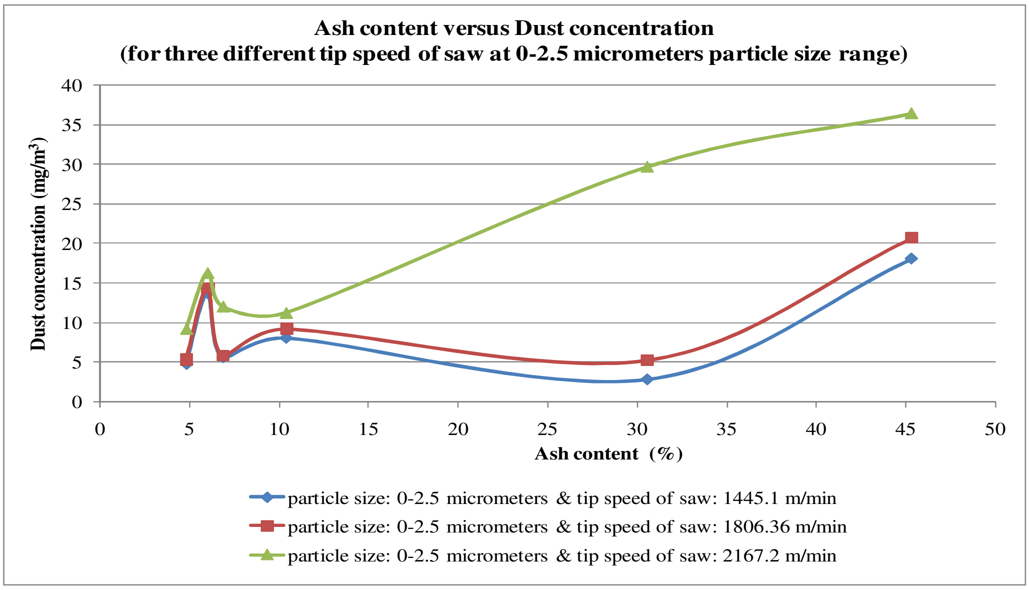

Figure 5.11 Ash content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

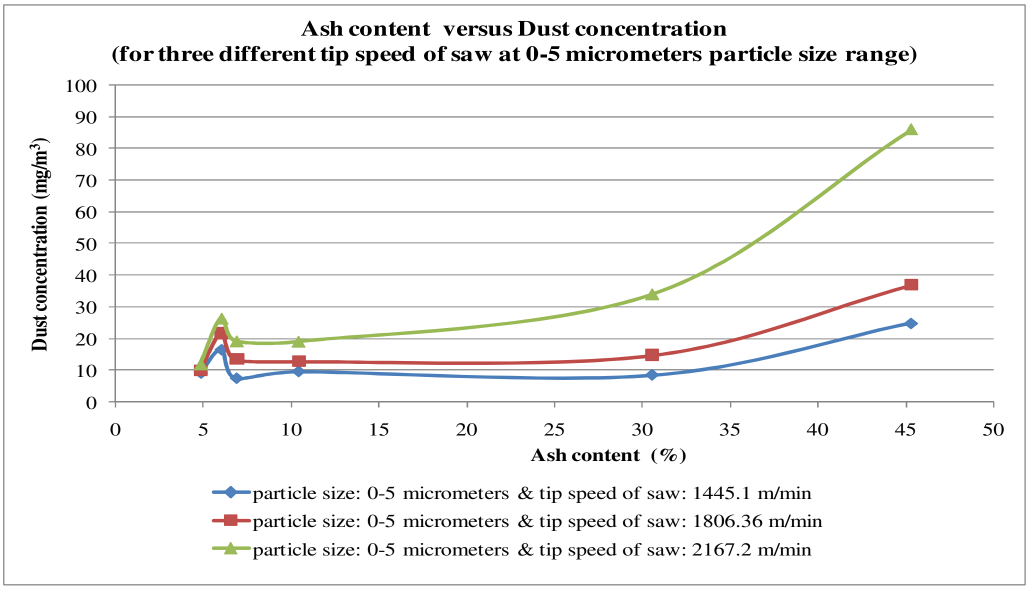

Figure 5.12 Ash content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

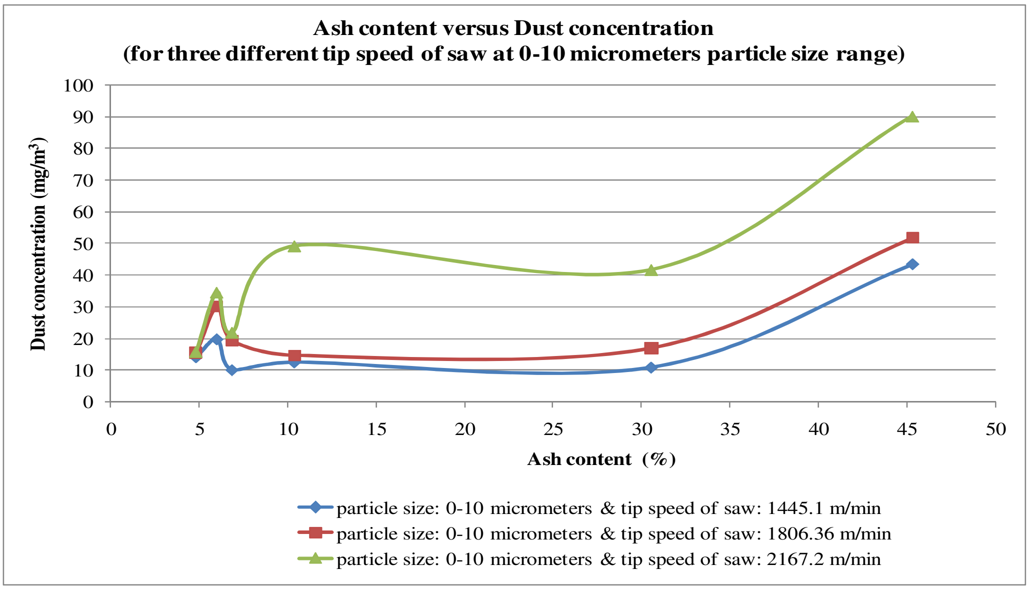

Figure 5.13 Ash content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

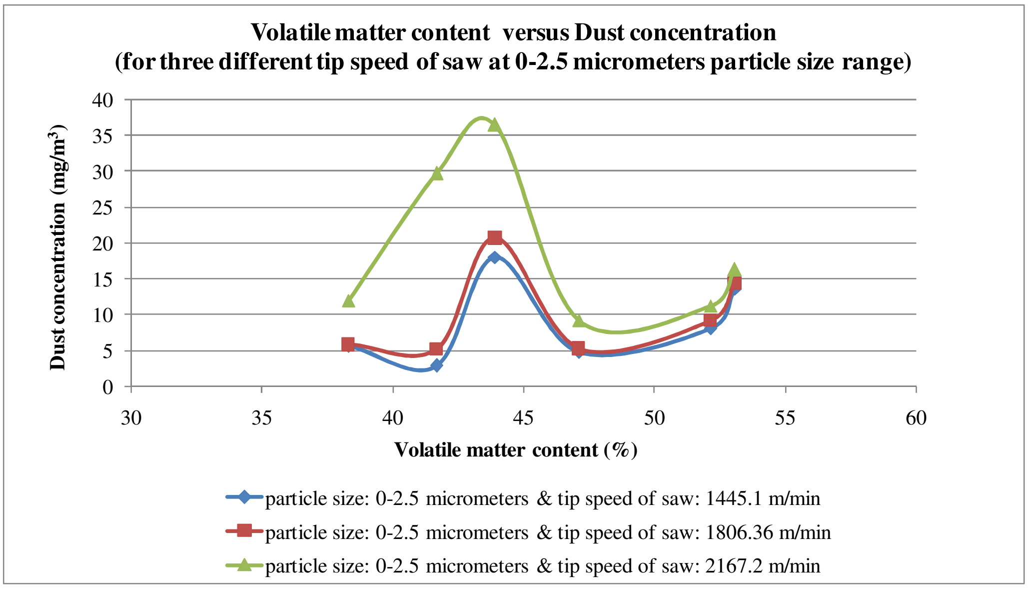

Figure 5.14 Volatile matter content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

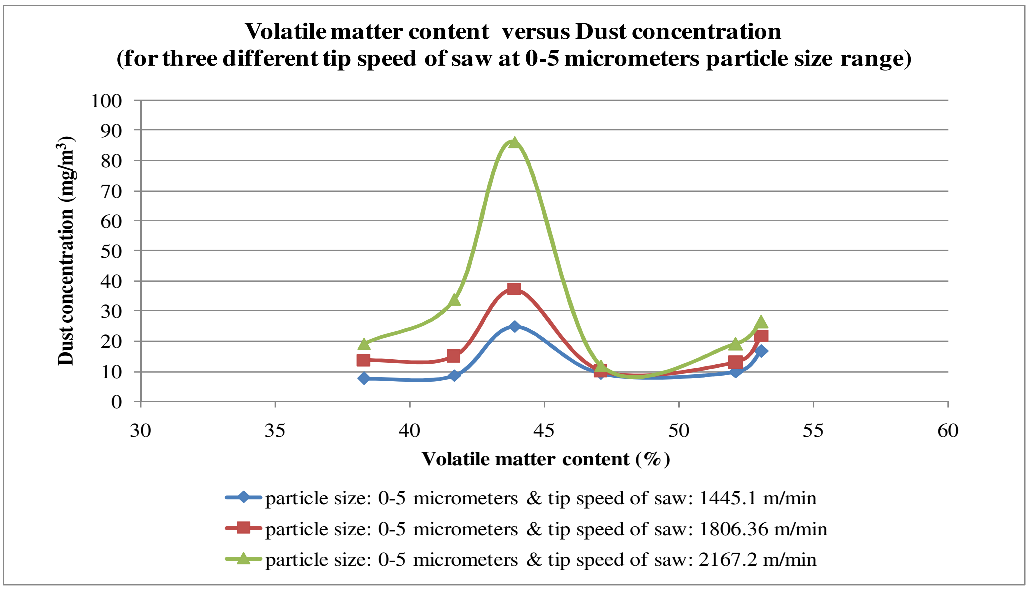

Figure 5.15 Volatile matter content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

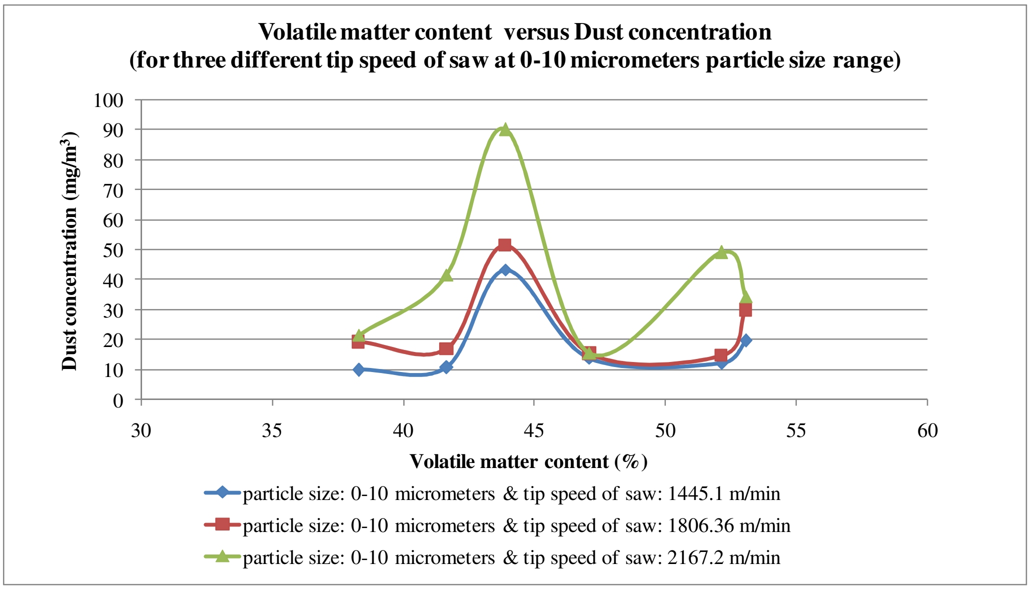

Figure 5.16 Volatile matter content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

Relationship between fixed carbon content of the lignite samples and dust concentrations can be seen in Figure 5.17 to Figure 5.19. Dust concentrations decreased in the range of fixed carbon from 4 to 21 percent for all particle size intervals and tip speed of saw and except one condition (measured concentration at 0-10 micrometers particle size range and 2167,2 m/min tip speed of saw), this trend appears to be followed by a rapid increase in the range of fixed carbon content from 24,478 to 30,216 percent. In general, from the related plots, although there are some exceptions, it can be concluded that a slight decrease in dust formation was observed as the fixed carbon content of coal increases.

Evaluation of the dust concentration data measured during the cutting process showed that there is not any significant relationship between moisture content of the coal and the amount of dust formed during cutting process (Figures 5.20 to 5.22).

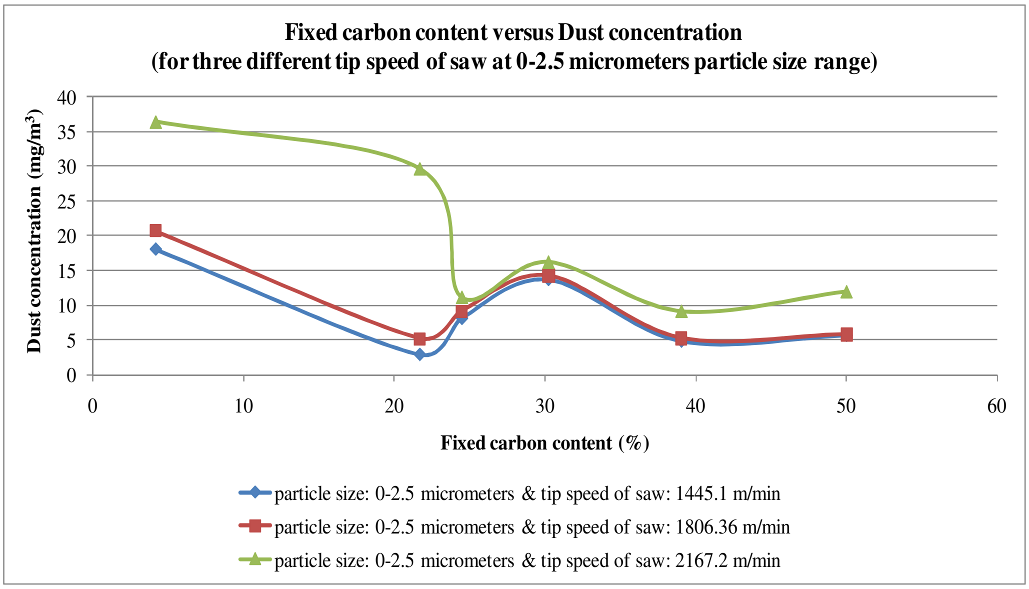

Figure 5.17 Fixed carbon content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

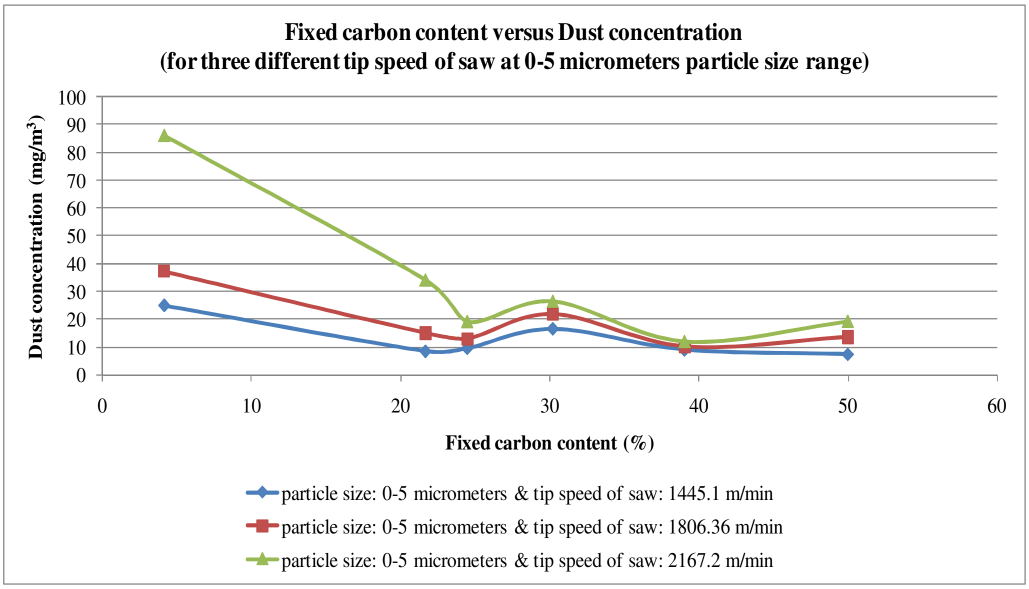

Figure 5.18 Fixed carbon content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

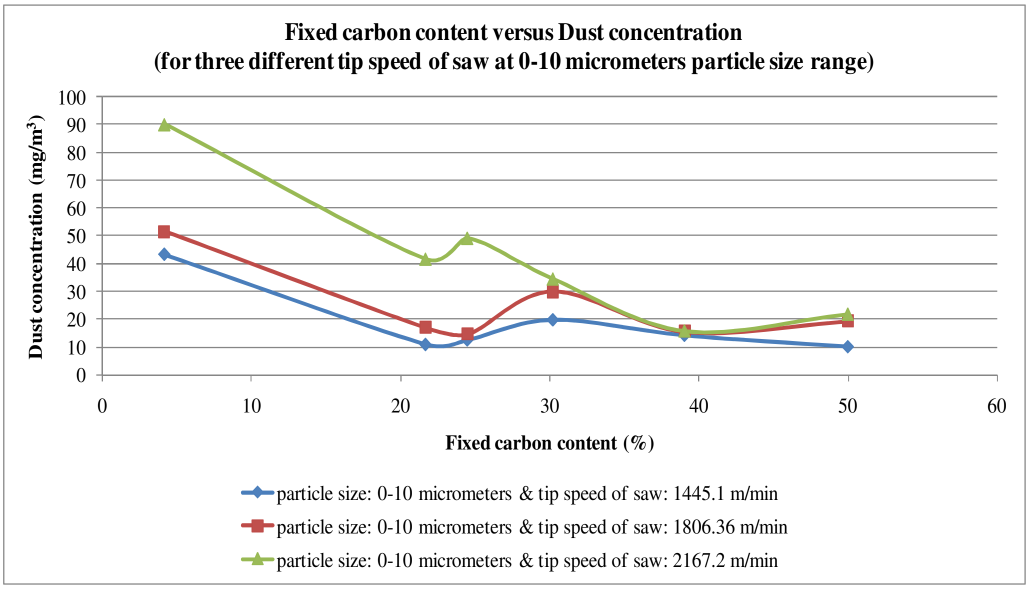

Figure 5.19 Fixed carbon content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

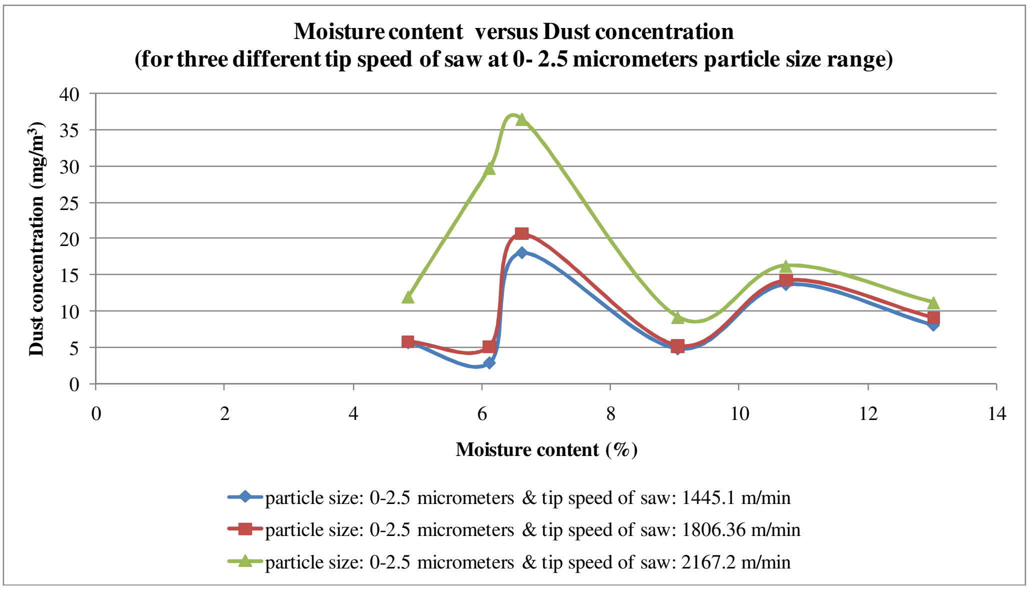

Figure 5.20 Moisture content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

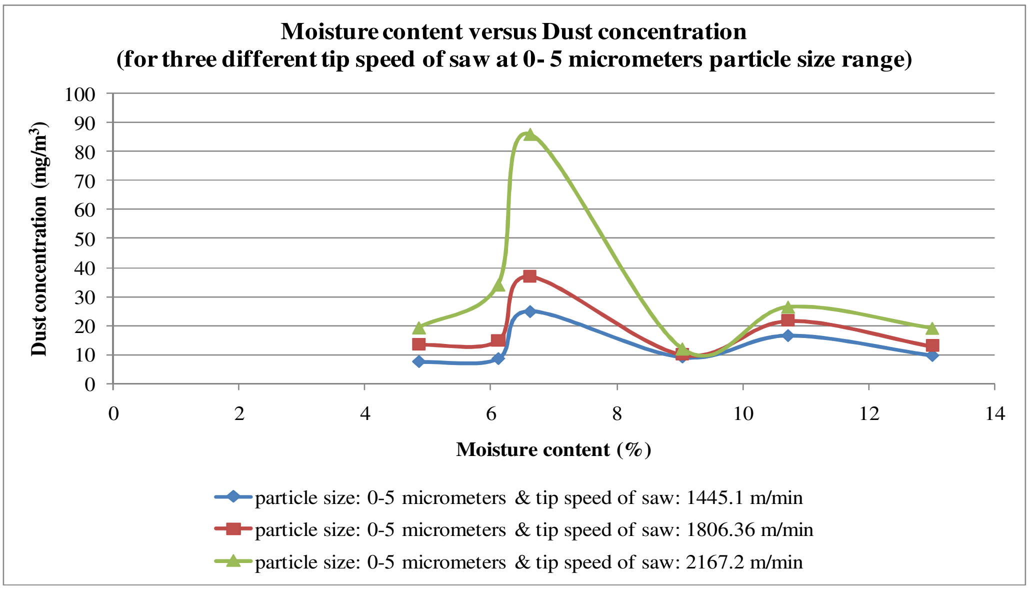

Figure 5.21 Moisture content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

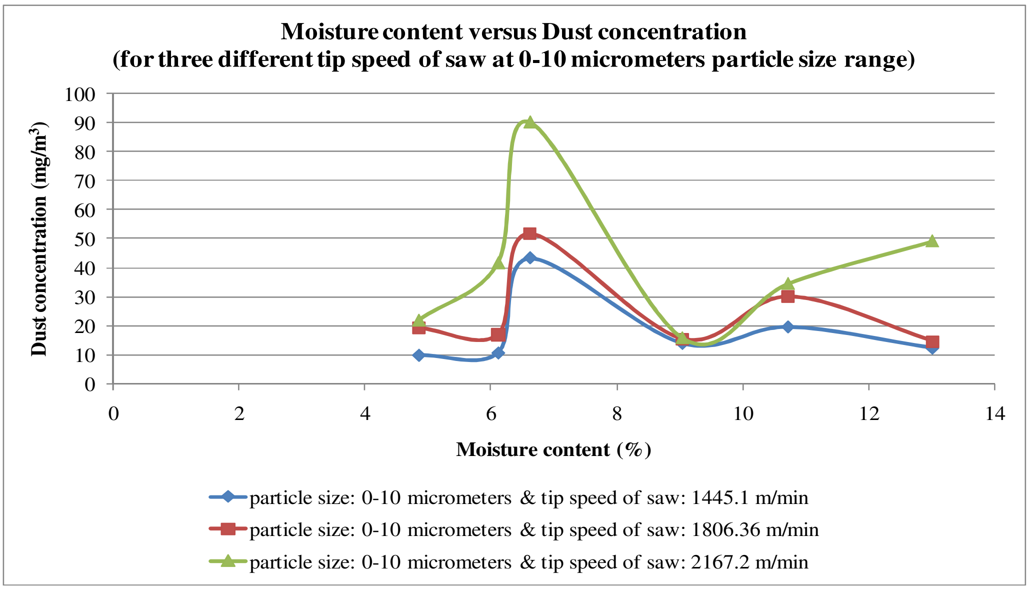

Figure 5.22 Moisture content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

5.5.4 The Relationship Between Some Petrographical Properties of Coal and Dust Concentration

Maceral content of all coal samples were given at Table 5.3. Since huminite is the most abundant portion of all coal samples, it is necessary to investigate the effect of this maceral on dust generation rate of the coal samples during the cutting action. Graphical representation of the relationship between this maceral group and dust concentration values for all particle size ranges and tip speed of saw can be seen from Figure 5.23 through Figure 5.25. Dust concentrations decrease in between percentages of 54 to 59 for huminite values. This trend is followed by a rapid increase in the range of huminite content from 70 to 74 percent for all cases. For all particle size intervals, dust concentrations decrease in the range of 74 to 80 percent of huminite content. As a conclusion, there is a slight decrease in dust formation as huminite content of coal increases.

Since high amounts of inertinite, especially fusinite in coal, cause the generation of very fine dust during mining, relationship between coal dust generation and occurence of this maceral group was also studied (Figure 26 to 28). For all cases, dust concentrations increase between 5 to 6 percent for inertinite content and reach to maximum point at 6 percent of inertinite content and then this trend is followed by a sharp decrease until the value of inertinite content reaches the 9 percent. Since fusinite content of the samples are very close to each other it is very difficult to understand the effect of this structure on dust generation rate during the experiments. Although some minor relations were detected from the results of the experiments, in generally, it was observed that there is no significant relationship between inertinite and amount of dust formation. Since liptinite content of the coal samples are very close to each other, plots of this maceral group were not reviewed.

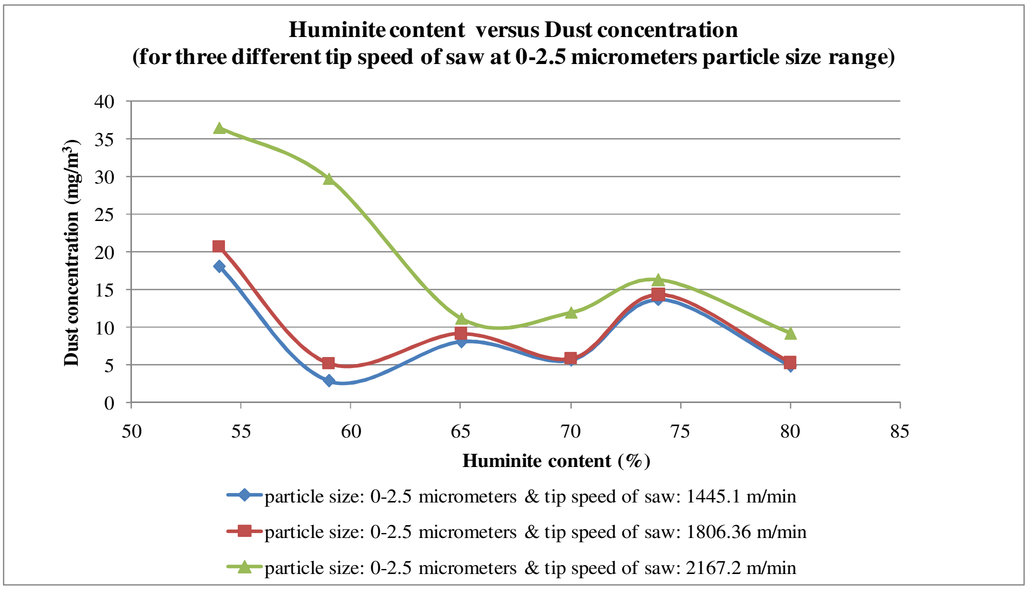

Figure 5.23 Huminite content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

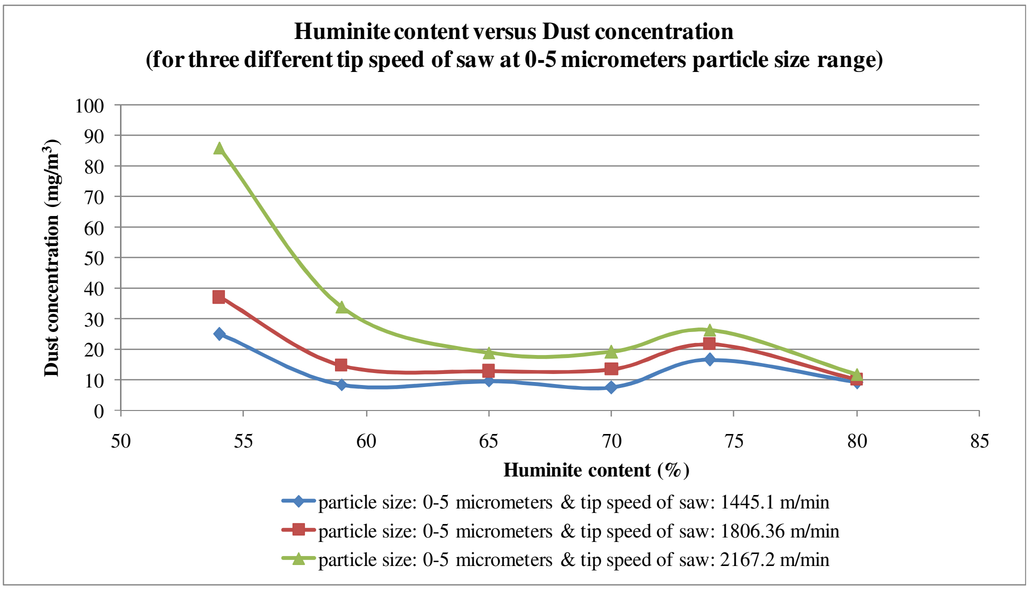

Figure 5.24 Huminite content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

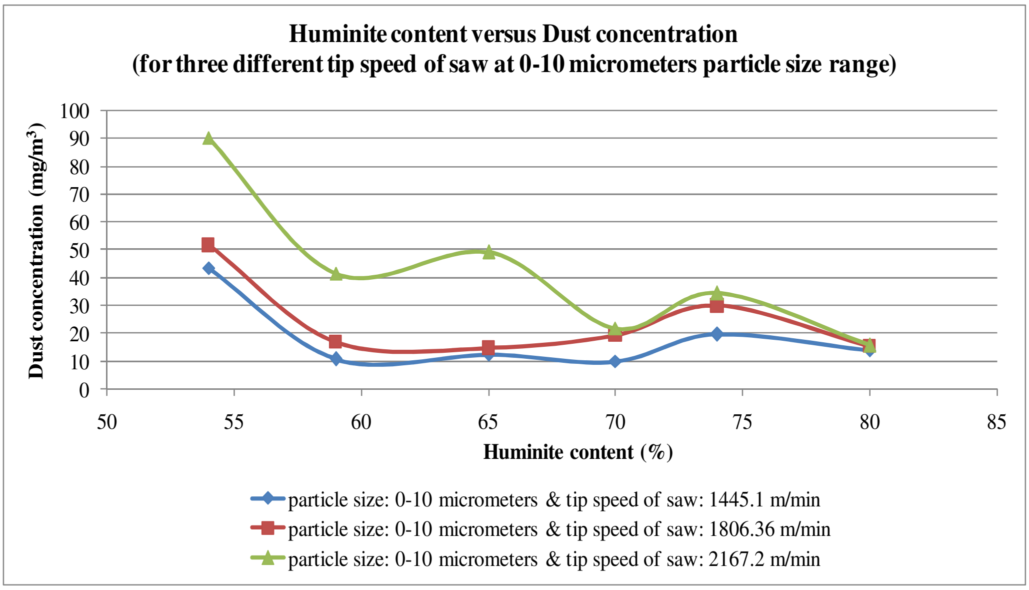

Figure 5.25 Huminite content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

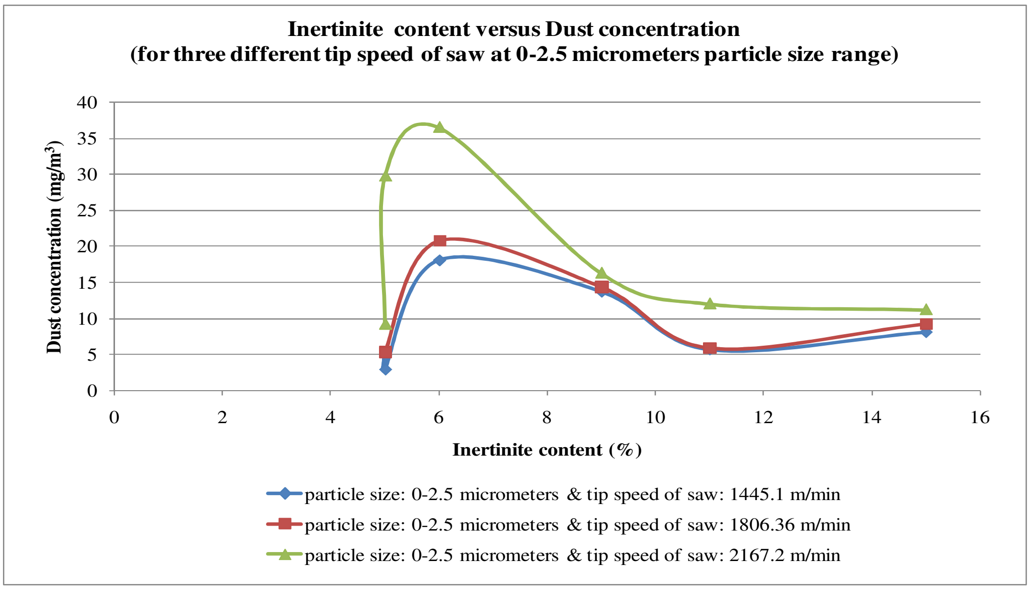

Figure 5.26 Inertinite content versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

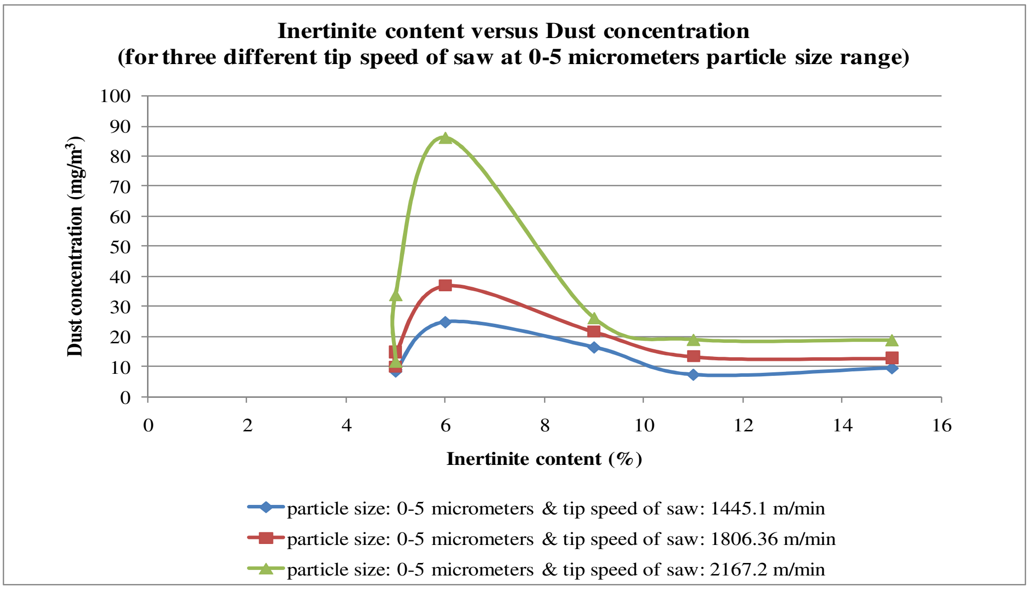

Figure 5.27 Inertinite content versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

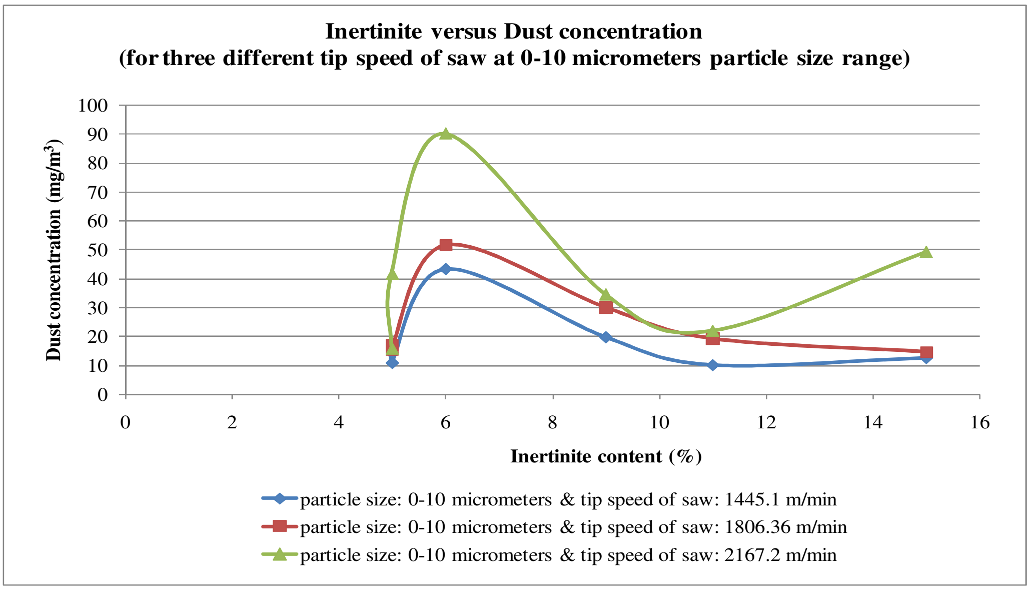

Figure 5.28 Inertinite content versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

5.5.5 The Relationship Between Rank of Coal and Dust Concentration

Since most of the studies used vitrinite reflectance, fuel ratio, HGI and some other properties of coal in order to describe the rank of it, the relationship between coal dust generation and vitrinite reflectance and fuel ratio of samples were also studied.

Dust concentrations increase in the range of vitrinite reflectance from 0.444 to 0.449 percent for all particle size intervals and at this point, they reach maximum value and then decrease until the vitrinite reflectance value of 0.506 (Figure 5.29 to 5.31). Although some of the researchers stated that amount of dust generated increase with coal rank, some of them do not agree with these researchers. As stated earlier, one of the studies done by Organiscak et al. (1992) showed that lower rank bituminous coals tended to produce more dust. Therefore, decreasing of dust concentration with further increase in rank of coal in the range of vitrinite reflectance values of 0.449 to 0.506, is not surprising. As vitrinite reflectance values increases, amount dust formation gets lower and lower for the vitrinite reflectance values higher than 0.45%. Figures from 5.32 to 5.34 show the relationship between dust concentration and fuel ratio of the coal samples. As can be seen from these figures, there is no significant trend between the dust concentration values and the fuel ratio. Therefore, significant relationship between fuel ratio and amount of dust generated during the cutting process of coal samples could not be detected during this study.

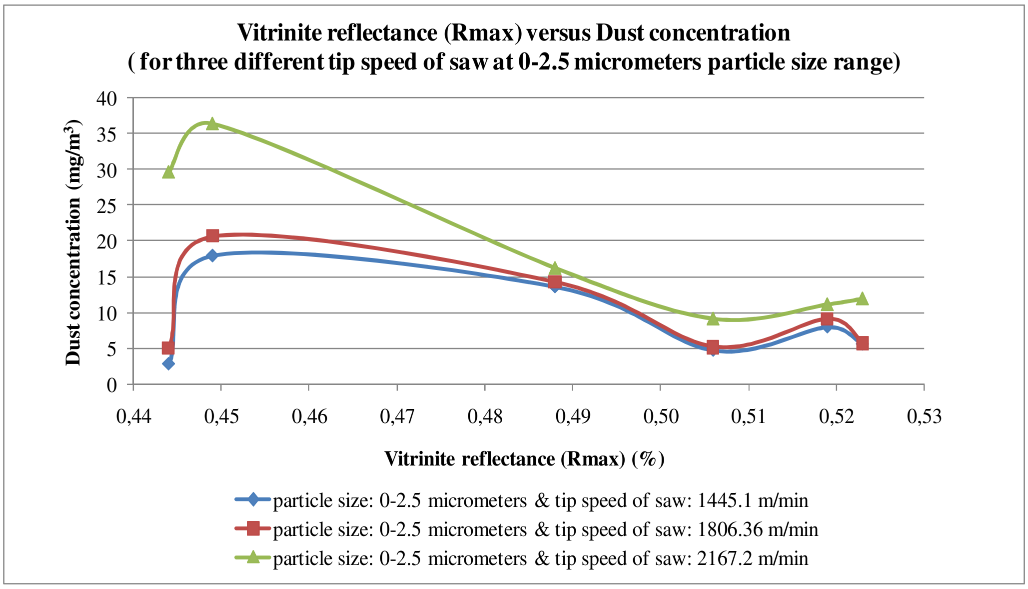

Figure 5.29 Rmax versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

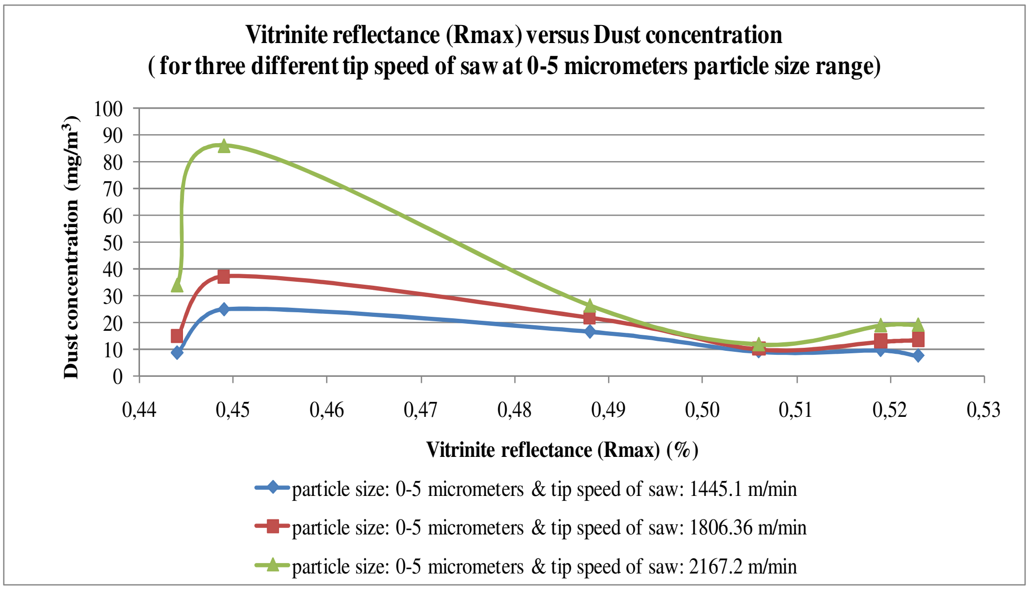

Figure 5.30 Rmax versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

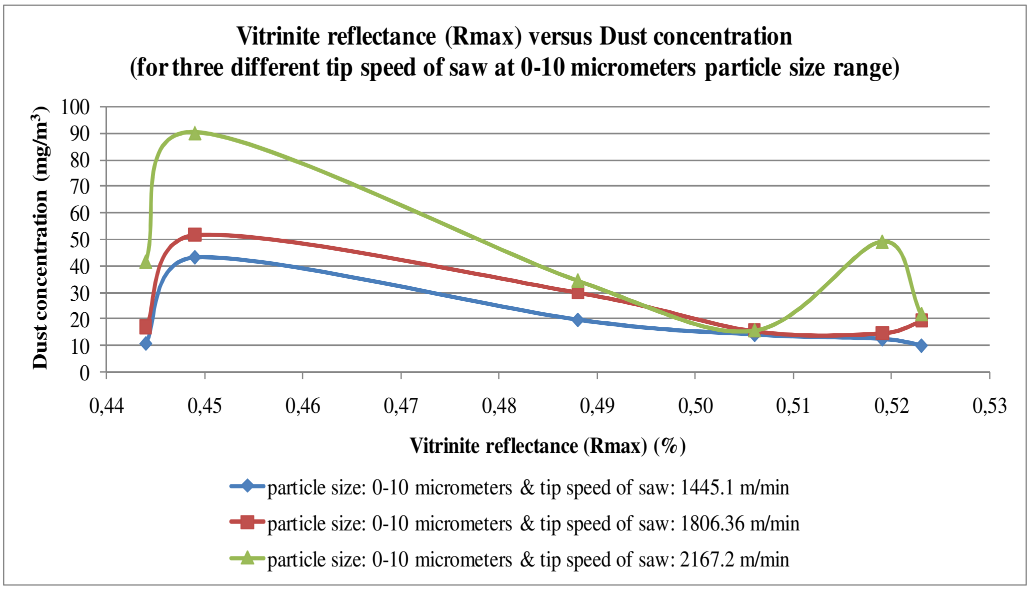

Figure 5.31 Rmax versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

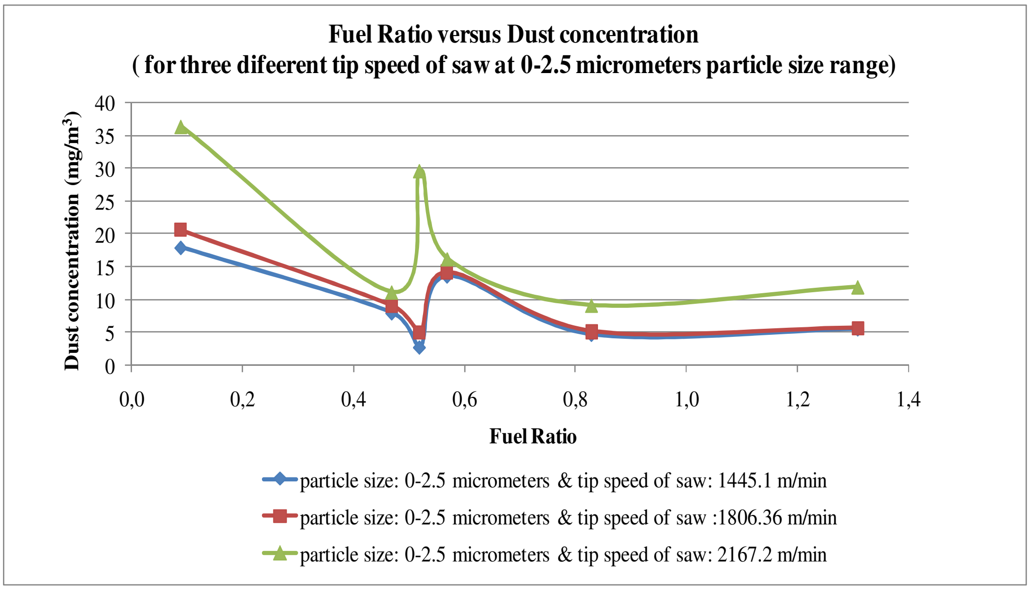

Figure 5.32 Fuel ratio versus dust concentration (three different tip speed of saw at 0-2.5 micrometers particle size range)

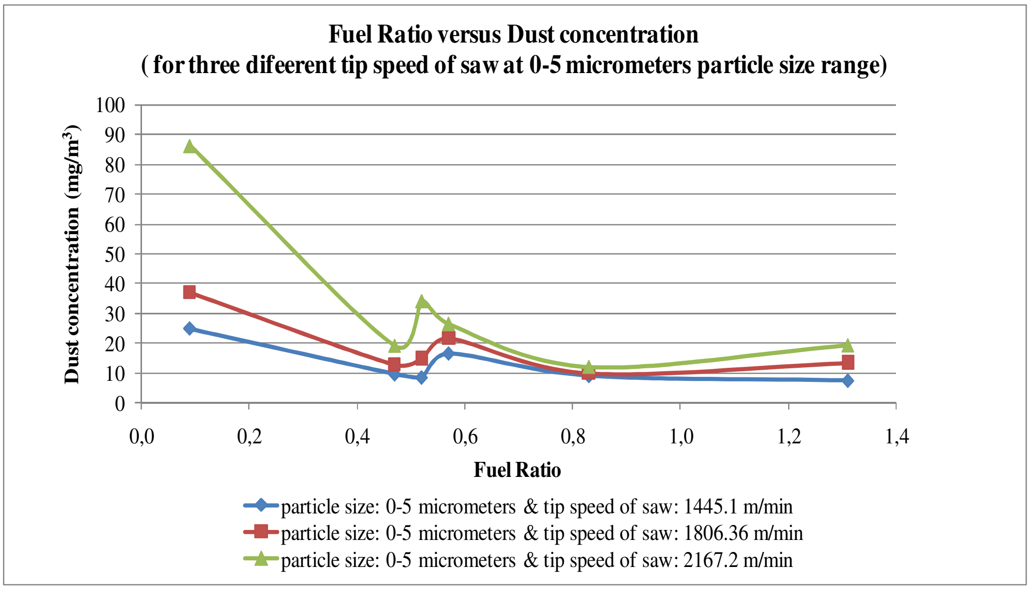

Figure 5.33 Fuel ratio versus dust concentration (three different tip speed of saw at 0-5 micrometers particle size range)

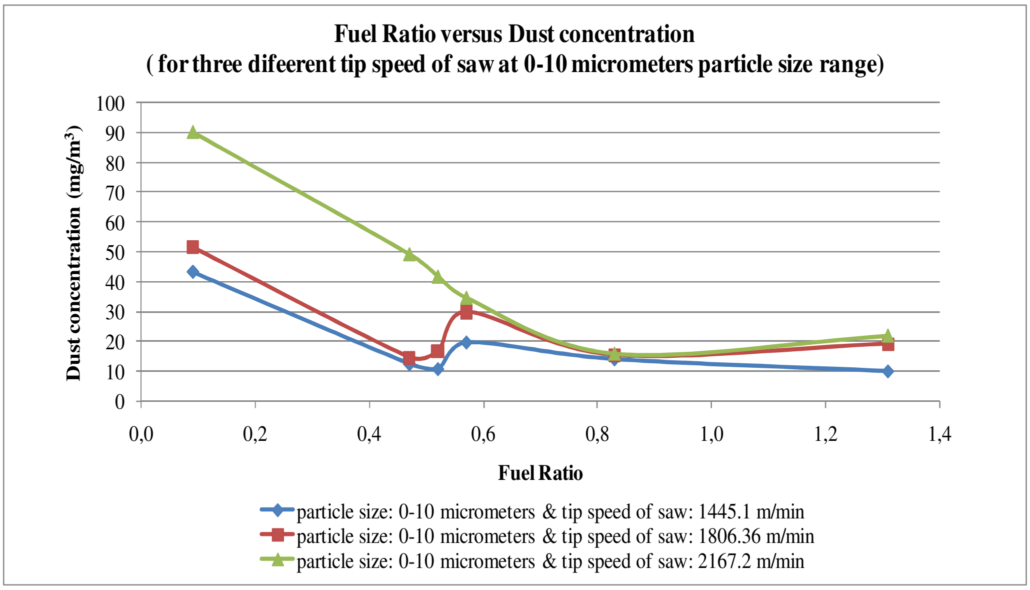

Figure 5.34 Fuel ratio versus dust concentration (three different tip speed of saw at 0-10 micrometers particle size range)

5.6 Dust Concentration Measurement Results at Small Scale Saw Mechanism

Second group of dust measurements were done in so called small scale saw experiment set. For this set of experiments, only Beypazarı upper seam samples were used. During the measurements only 0-10 μ size range was considered. The results of the experiments can be shown at Table 5.7.

As stated in Chapter 4, nine different table advancing velocity and five different tip speed were applied during the cutting of coal samples. This system was set to understand the effect of the advancing velocity on dust generation. The results of these measurements are given in Table 5.7. Since dust concentrations measured at 210,6 m/min tip speed of saw for some of the table advancing velocities were nearly zero, these measurements were called as "not applicable" as seen in Table 5.7. It can be seen in Figure 5.35, for all dust concentration measurement cases, these values decrease between the table advancing velocity range of 45 mm/min to 90 mm/min. Also for all different advancing velocities, dust concentrations did not change at 210,6 m/min tip speed of saw. Although some minor relations were detected between dust concentration and table advancing velocity from the scatter plot, this is not enough to obtain general remarks. Results of the measurements on the small scale saw system showed that there was no significant relationship between the amount of dust generated and table advancing velocity. However, this relationship was also studied by using statistical analysis and results of this study will be given in next section.

Table 5.7 Average dust concentration measurement results at the small scale saw system

Average dust concentration (mg/m^3)	**Table advancing velocity (mm/min)**	**Tip speed of saw (m/min)**
Not Applicable	11,2	210,6
Not Applicable	16,0	
Not Applicable	22,4	
Not Applicable	31,5	
Not Applicable	45,0	
Not Applicable	63,0	
1,216	90,0	
1,039	125,0	
1,014	180,0	

Table 5.7 (continued)

Average dust concentration (mg/m^3)	**Table advancing velocity (mm/min)**	**Tip speed of saw (m/min)**
5,670	11,2	334,2
5,759	16,0	
6,991	22,4	
5,799	31,5	
4,281	45,0	
2,082	63,0	
0,953	90,0	
1,025	125,0	
3,630	180,0	
11,101	11,2	527,4
10,881	16,0	
9,953	22,4	
9,636	31,5	
9,955	45,0	
9,319	63,0	
7,100	90,0	
4,556	125,0	
1,512	180,0	
11,254	11,2	847,8
10,035	16,0	
7,516	22,4	
10,851	31,5	
12,783	45,0	
11,440	63,0	
9,642	90,0	
3,587	125,0	
6,137	180,0	

Table 5.7 (continued)

Average dust concentration (mg/m^3)	Table advancing velocity (mm/min)	Tip speed of saw (m/min)
14,921	11,2	1319,4
13,026	16,0	
13,375	22,4	
9,911	31,5	
10,988	45,0	
9,455	63,0	
6,685	90,0	
4,396	125,0	
15,266	180,0	

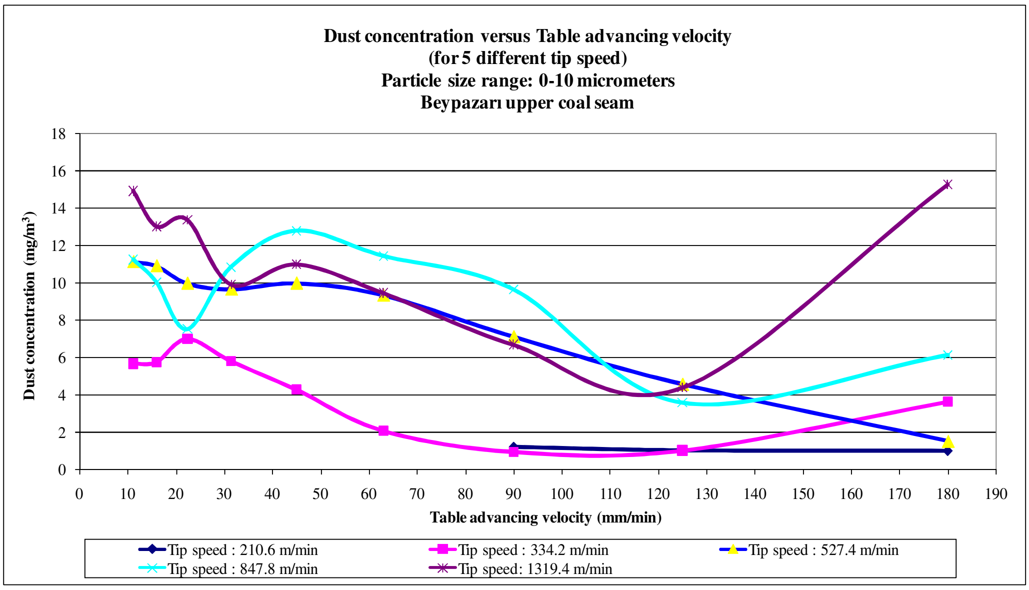

Figure 5.35 Dust concentration versus table advancing velocity

5.7 Statistical Analysis of the Measurements

In order to determine the relationships between the dust concentration and some of the properties of the coal samples and operating parameters, statistical analysis applications were also used in this study.

5.7.1 Correlation Analysis

Correlation analysis were applied for both dust concentration measurements obtained from small and large scale saw system. In following sections, results of these analysis were discussed.

5.7.1.1 Correlation Analysis for Measurements at Large Scale Saw System

The inter-relations between some of the coal sample properties and amount of dust generation were investigated by using the Pearson product moment coefficient of correlation (Table 5.8). The correlation coefficient between average dust concentration and moisture (-0,119) was found as statistically insignificant. This result is in agreement with the experimental results explained at Section 5.5.3. The correlation coefficients between dust concentration and the volatile matter (-0,23) and inertinite (-0,174) content of the lignite samples were also statistically insignificant.

The correlation coefficients between average dust concentration and HGI (0,513), ash content (0,556), fuel ratio (0,507), huminite (-0,48) and vitrinite reflectance (-0,440) were statistically significant at the 1% level. This means that amount of dust generated increases with its HGI value. This result is consistent with the study of Baafi (1977) and Moore (1986). Although the relationship between dust concentration and fuel ratio statistically significant, as stated Section 5.5.5, same relationship cannot be observed experimentally.

Although some fluctuations were detected for the relationship between ash content and dust concentration (Figure 5.11 to Figure 5.13) in Section 5.5.3, general trend shows that dust concentration increases with increasing ash content of the samples and this experimental result is also consistent with the results of the correlation analysis.

As stated in Section 5.5.4, since huminite is the most abundant maceral group for all lignite samples (Table 5.3), it is important to determine the effect of this maceral group on dust generation. According to correlation analysis, dust concentration and huminite content of the samples are inversely proportional. Although there are some exceptions for some intervals of the huminite content of the lignite samples, the statistical results are supported by the experimental results (Figure 5.23 to 5.25).

The correlation coefficient between average dust concentration and tip speed of saw (0,421) was significant at the 1% level. This results showed that average dust concentration and tip speed of saw are directly proportional and dust concentration increases with increasing tip speed of saw and experimental results (Figure 5.7) are also in agreement with the statistical ones.

Some of the properties of lignite samples were also very highly correlated with each other. Some of them are ash and HGI (0,957), ash and huminite (-0,904), ash and fuel ratio (-0,713), vitrinite reflectance and ash (-0,858), vitrinite reflectance and fixed carbon (0,763), fixed carbon content and ash content (-0,853), fixed carbon content and huminite content (0,784), fixed carbon content and fuel ratio (0,972), vitrinite reflectance and HGI (-0,800). Results of the correlation analysis were used to find an equation between dust concentration and properties of coal with the help of regression analysis.

Table 5.8. Correlation analysis of the parameters used at the large scale saw mechanism experiments

		ADC	PS	TS	M	VM	FC	Ash	H	L	I	Rmax	FR	HGI
Ave. Dust Conc. (ADC)	Pearson correlation	1	,356**	,421**	-,119	-,023	-,561**	,556**	-,480**	-,357**	-,174	-,440**	-,507**	,513**
	Sig. (2-tailed)	,000	,008	,002	,390	,868	,000	,000	,000	,008	,208	,001	,000	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Particle Size (PS)	Pearson correlation	,356**	1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Sig. (2-tailed)	0,008		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Tip speed of saw (TS)	Pearson correlation	,421**	,000	1	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000
	Sig. (2-tailed)	,002	1,00		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Moisture (M)	Pearson correlation	-,119	,000	,000	1	,952**	-,104	-,421**	,309*	,563**	,526**	,374**	-,308*	-,658**
	Sig. (2-tailed)	,390	1,00	1,00		,000	,456	,002	,023	,000	,000	,005	,024	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Volatile matter (VM)	Pearson correlation	-,023	,000	,000	,952**	1	-,187	-,351**	,321*	,323*	,348**	,210	-,403**	-,585**
	Sig. (2-tailed)	,868	1,000	1,000	,000		,175	,009	,018	,017	,010	,127	,003	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Fixed Carbon (FC)	Pearson correlation	-,561**	,000	,000	-,104	-,187	1	-,853**	,784**	,404**	,244	,763**	,972**	-,673**
	Sig. (2-tailed)	,000	1,000	1,000	,456	,175		,000	,000	,002	,076	,000	,000	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54

Table 5.8 (continued)

		ADC	PS	TS	M	VM	FC	Ash	H	L	I	Rmax	FR	HGI
Ash	Pearson correlation	,556**	,000	,000	-,421**	-,351**	-,853**	1	-,904**	-,596**	-,448**	-,858**	-,713**	,957**
	Sig. (2-tailed)	,000	1,000	1,000	,002	,009	,000		,000	,000	,001	,000	,000	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Huminite (H)	Pearson correlation	-,480**	,000	,000	,309*	,321*	,784**	-,904**	1	,249	,068	,683**	,632**	-,836**
	Sig. (2-tailed)	,000	1,000	1,000	,023	,018	,000	,000		,070	,627	,000	,000	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Liptinite (L)	Pearson correlation	-,357**	,000	,000	,563**	,323*	,404**	-,596**	,249	1	0,922**	,801**	,341*	-,663**
	Sig. (2-tailed)	,008	1,000	1,000	,000	,017	,002	,000	,070		,000	,000	,012	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Inertinite (I)	Pearson correlation	-,174	,000	,000	,526**	,348**	,244	-,448**	,068	,922**	1	,693	,204	-,522**
	Sig. (2-tailed)	,208	1,000	1,000	,000	,010	,076	,001	,627	,000		,000	,138	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Rmax	Pearson correlation	-,440**	,000	,000	,374**	,210	,763**	-,858**	,683**	,801**	,693**	1	,685	-,800**
	Sig. (2-tailed)	,001	1,000	1,000	,005	,127	,000	,000	,000	,000	,000		,000	,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
Fuel Ratio (FR)	Pearson correlation	-,507**	,000	,000	-,308*	-,403**	,972**	-,713**	,632**	,341*	,204	,685**	1	-,493**
	Sig. (2-tailed)	,000	1,000	1,000	,024	,003	,000	,000	,000	,012	,138	,000		,000
	N	54	54	54	54	54	54	54	54	54	54	54	54	54
HGI	Pearson correlation	,513**	,000	,000	-,658**	-,585**	-,673**	,957**	-,836**	-,663**	-,522	-,800**	-,493**	1
	Sig. (2-tailed)	,000	1,000	1,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	
	N	54	54	54	54	54	54	54	54	54	54	54	54	54

**. Correlation is significant at the 0.01 level (2-tailed).

5.7.1.2 Correlation Analysis for Measurements at Small Scale Saw System

As can be seen from Table 5.9, average dust concentration and tip speed of saw (0,655) are highly correlated, same conclusion can be drawn for the correlation between average dust concentration and table advancing velocity (-0,523). Since only one lignite sample was used during the experiments at the small scale saw system, other properties of coal are same, therefore, correlations between each of them are not investigated in this study.

Table 5.9 Correlation analysis of the parameters used at the small scale saw mechanism experiments

		Ave. Dust Conc.	Table advancing velocity	Tip speed of saw
Ave. Dust Conc.	Pearson correlation	1	-0,523**	0,655
	Sig. (2-tailed)		0.001	0,000
	N	39	39	39
Table advancing velocity	Pearson correlation	-0,523**	1	-0,120
	Sig. (2-tailed)	0,001		0,465
	N	45	39	39
Tip speed of saw	Pearson correlation	0,655**	-0,120	1
	Sig. (2-tailed)	0,000	0,465	
	N	39	39	39
**. Correlation is significant at the 0.01 level (2-tailed).				

5.7.2 Regression Analysis

Regression analysis was used to obtain an equation between dust concentration and some properties of coal. With the help of this equation, dust generation potential of the different coal seams can be determined in the early stage of the mining and this provides the time to take the necessary measures at beginning of the mining activities.

Four models were found by using the data obtained from the experiments to express the relationship between dust concentration and other variables at studied conditions. First three models were established by using the measurements obtained from large scale saw system experiments and the Model 4 was established by using the experimental results of the small scale saw system mechanism. Linear regression analysis was applied to establish Model 1, Model 2 and Model 4. However, nonlinear regression analysis was used to obtain Model 3.

At the Model 1, tip speed of saw was included in the regression equation (Equation 5.1) and this equation was able to explain 65,2 percent of the variation in data. Results of this model can be seen in Table 5.10. The output shows the results of fitting a multiple linear regression model to describe the relationship between average dust concentration and 4 independent variables. At this model, the P-value in the ANOVA table is less than 0.05, this means that there is a statistically significant relationship between the variables at the 95,0% confidence level. The equation of the fitted model is

$$DC = -31{,}954 + 1{,}996 \times (PS) + 0{,}025 \times (TS) - 0{,}481 \times (FC) + 0{,}201 \times (HGI) \qquad (5.1)$$

where,

DC: Dust concentration at stated particle size (mg/m^3)

PS: Particle size of the dust particles (micrometer),

TS: Tip speed of saw (m/min),

FC: Fixed carbon content of the lignite sample (%),

HGI: Hardgrove grindability index of lignite coal.

Table 5.10 Summary of the Regression Analysis of the Model 1

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0,808	0,652	0,624	10,812879

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10756,113	4	2689,028	22,999	0,000
	Residual	5728,999	49	116,918		
	Total	16485,112	53			

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std.Error	Beta		
1	(Constant)	-31,954	12,208		-2,617	0,012
	Particle size	1,996	0,472	0,356	4,230	0,000
	tip speed of saw	0,025	0,005	0,421	4,998	0,000
	HGI	0,201	0,092	0,248	2,179	0,034
	fixed carbon	-0,481	0,139	-0,394	-3,461	0,001

Fitting a linear regression model process was applied without using tip speed of saw as a variable for Model 2. Table 5.11 shows the results of fitting a multiple linear regression model to describe the relationship between average dust concentration and 3 independent variables. Since the P-value is less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level at Model 2.

The equation of the fitted model is

$$DC = 5{,}584 + 1{,}996 \times (PS) + 0{,}282 \times (HGI) - 15{,}703 \times (FR) \qquad (5.2)$$

where,

DC: Dust concentration at stated particle size (mg/m^3)
PS: Particle size of the dust particles (micrometer),
HGI: Hardgrove grindability index of lignite coal.
FR: Fuel Ratio content of the lignite sample (%),

and this equation was able to explain 47.5 percent of the variation in data. Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level.

As stated earlier, relationship between amount of coal dust generated and properties of coal are very complex and at the same time lots of parameters (environmental conditions, operating parameters, laboratory conditions etc.) should be taken into consideration, therefore it is very difficult to express these relationship only using linear regression method. Because of this complexity, nonlinear regression was also applied in this study to fit the best representative model to measurements of the experiments. At Model 3 , tip speed of saw and particle size was included in the equation of the model. Table 5.12 shows the results of the nonlinear regression model to describe the relationship between average dust concentration and some of the operating parameters and coal properties. The equation of the fitted model is

$$DC = \frac{-0{,}534 \times (Hum) + 8{,}587 \times (PS) + 1{,}146 \times 10^{-8} \times (TS)^3}{\sqrt{(FC)}} \tag{5.3}$$

where,

DC: Dust concentration at stated particle size (mg/m^3)
Hum: Huminite content of lignite sample (%),
PS: Particle size of the dust particles (micrometer),
TS: Tip speed of saw (m/min),
FC: Fixed carbon content of the lignite sample (%).

and this equation was able to explain 84.5 percent of the variation in data.

Table 5.11 Summary of the Regression Analysis of the Model 2

Model Summary					
Model		R	R Square	Adjusted R Square	Std. Error of the Estimate
2		0,690	0,475	0,444	13,150898

ANOVA						
Model		Sum of Squares	df	Mean Square	F	Sig.
2	Regression	7837,806	3	2612,602	15,106	0,000
	Residual	8647,305	50	172,946		
	Total	16485,112	53			

Coefficients						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std.Error	Beta		
2	(Constant)	5,584	7,929		0,704	0,485
	Particle size	1,996	0,574	0,356	3,478	0,001
	HGI	0,282	0,096	0,348	2,956	0,005
	fuel ratio	-15,703	5,513	-0,335	-2,848	0,006

Table 5.12 Summary of the Regression Analysis of the Model 3

Parameter Estimates				
Parameter	Estimate	Std Error	95 % Confidence Interval	
			Lower Bound	Upper Bound
a	-0,534	1,177	-2,900	1,832
b	8,587	0,000	8,587	8,587
c	1,146E-8	0,177	-0,355	0,355
ANOVA				
Source	Sum of Squares	df	Mean Squares	
Regression	37192,858	5	7438,572	
Residual	2563,259	49	52,311	
Uncorrected Total	39756,117	54		
Corrected Total	16485,112	53		
R squared = 84.5 %				

Model 4 includes the regression analysis of the experimental results of the small scale system, summary of this analysis can be seen in Table 5.13. Equation 5.4 was able to explain 62.8 percent of the variation in data. The summary shows the results of fitting a multiple linear regression model to describe the relationship between average dust concentration and two independent variables. At this model, the P-value in the ANOVA table is less than 0.05, this means that there is a statistically significant relationship between the variables at the 95.0% confidence level. The equation of the fitted model is

$$DC = 5{,}302 - 0{,}034 \times (TAV) + 0{,}006 \times (TS) \qquad (5.4)$$

where,

DC: Dust concentration (mg/m^3)
TAV: Table advancing velocity of the small scale system (mm/min),
TS: Tip speed of saw (m/min).

Table advancing velocity in Equation 5.4 actually can be considered as the shearer advancing velocity and with the help of this equation, dust generation potential of the lignite seams can be determined in real life. Since tip speed of saw symbolised the shearer drum rotational speed, same comment can also be given for this variable.

Table 5.13 Summary of the Regression Analysis of the Model 4

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
4	0,793	0,628	0,608	2,631167

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
4	Regression	421,429	2	210,715	30,437	0,000
	Residual	249,229	36	6,923		
	Total	670,659	38			

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std.Error	Beta		
4	(Constant)	5,302	1,086		4,882	0,000
	Table advancing velocity	-0,034	0,008	-0,45	-4,400	0,000
	Tip speed of saw	0,006	0,001	0,600	5,867	0,000

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Dust is a very important problem for mining industry. Dust prevention should have the first priority in mining activities due to the fact that it is closely related to the human health. On the other hand, it is management's duty to provide a healthy working environment. Recently, by using modern technologies, new dust prevention methods have been developed. Owner of the mines should follow new tecnologies and apply the most suitable methods for their mines.

This study investigates the relationship between some of the physical, chemical, petrographical, operating parameters and amount of dust generated. As a result of this study, the following conclusions are drawn.

1. Effect of the tip speed of saw on dust generation was investigated. For all particle size ranges, dust concentration increases with increasing tip speed of saw. For 0-2.5 micrometers particle size range, very small increasing in dust concentration was detected when tip speed of saw increased from 1445,1 m/min to 1806,36 m/min. However, significant increase in dust concentration were measured for this particle size range when tip speed of saw was 2167,2 m/min. For respirable particle size range (0-5 micrometers) dust concentrations increased with increasing tip speed of saw. For 0-10 micrometers particle size range, again dust concentration values increased with rising tip speed of saw but amount of increase in dust concentration is higher when tip speed of saw was 2167,2 m/min. Almost all coal samples show similar trend when tip speed changes. This means that amount of increase in

dust concentration is not very significant when cutting tip speed of the saw is increased from 1445,1 m/min to 1806,36 m/min. But when tip speed of saw increases to 2167,2 m/min, dust concentration increases significantly.

2. The relationship between grindability and amount of dust generation was studied by using the Hardgrove grindability index. Measurements showed that as the HGI value gets higher than 50, there is a quite increase in the production of respirable dust.

3. Effect of the some chemical properties of the coal on dust generation was examined. Firstly, it has been observed that the formation of respirable dust has quite good positive correlation with coals having an ash content higher than 10 %. This means that higher ash content of the coal causes the generation of higher respirable coal dust. Secondly, experiments showed that as the fixed carbon content of the coal increased, a slight decrease in coal dust concentration was observed. Thirdly, during this study, it could not be obtained any significant relationship between dust concentration and volatile matter and moisture content of the samples.

4. Evaluation of the dust concentration measurements and petrographical properties of coal samples showed that there is a slight decrease in dust formation as huminite content of coal increases. For the another maceral group of inertinite, it could not be obtained any significant relationship between dust concentration and this maceral group.

5. Vitrinite reflectance and fuel ratio values were used in order to understand the relationship between coal rank and amount of dust generation. As vitrinite reflectance values increases (especially for $R_{max} > 0.45$ %), dust concentrations decreases significantly. This shows that as the maturation degree of the coal increases, amount of dust generation decreases.

6. Experiments on the small scale saw system showed that there was no significant relationship between the amount of dust generated and table advancing velocity.

7. Relations between dust concentration values and different variables (some of the chemical, petrographical and grindability properties and cutting operating parameters (tip speed of saw, table advancing velocity) were also examined statistically by using correlation and multiple regression analysis. Most of the results obtained from correlation analysis were consistent with the experimental ones. This means that correlation coefficent between average dust concentration and moisture, volatile matter and inertinite content of the coal samples were found as statistically insignificant which was same with experimental results. Similarly, correlation analysis also showed that HGI, ash content, particle size, tip speed of saw, huminite content, fuel ratio and vitrinite reflectance were correlated with the dust concentration values. In addition to these, correlation analysis of the dust concentration values obtained from the small scale experiment set-up showed that relationship between table advancing velocity and dust concentration values were statistically significant at 1% level. Finally, to measure the dust generation potential of the lignite seam, four regression equations were obtained by using different variables.

8. This study can be improved by using different dust generation mechanisms like drilling, grinding and crushing in laboratory experiments. In addition, using different statistical analysis can also be useful to determine the relations between dust concentration and other variables.

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APPENDIX A

EXAMPLES OF THE SOME MEASUREMENTS

During this study, average dust concentration values were used. For each of the tip speed and particle size range, various experiments were conducted and then average of them was used during the discussion. Some examples of this experimental data are given in Table A.1-A.4.

Table A1. Data of the first experiment of the dust concentration measurements for Soma coal with 0-2.5 micrometers particle size range and 1445,1 m/min tip speed of saw (T = Time interval; C = Average dust concentration)

T (second)	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**
1	0,619	**17**	4,812	**33**	3,393	**49**	3,805	**65**	5,517
2	2,276	**18**	4,986	**34**	3,326	**50**	3,802	**66**	4,679
3	4,439	**19**	4,135	**35**	3,445	**51**	3,636	**67**	4,276
4	6,010	**20**	3,682	**36**	3,703	**52**	3,362	**68**	5,275
5	6,254	**21**	4,001	**37**	3,988	**53**	3,302	**69**	5,039
6	6,125	**22**	4,101	**38**	4,036	**54**	3,312	**70**	5,184
7	5,203	**23**	3,710	**39**	3,952	**55**	3,403	**71**	6,389
8	4,639	**24**	4,393	**40**	4,611	**56**	3,251	**72**	6,504
9	4,590	**25**	4,338	**41**	4,044	**57**	3,581	**73**	5,527
10	4,700	**26**	4,214	**42**	3,918	**58**	3,474	74	8,283
11	4,864	**27**	4,071	**43**	3,710	**59**	3,508	**75**	**10,215**
12	4,687	**28**	4,624	**44**	4,393	**60**	3,994	**Average : 4,442**	
13	4,849	**29**	4,645	**45**	4,185	**61**	4,102		
14	5,009	**30**	4,830	**46**	4,130	**62**	4,314		
15	4,960	**31**	4,018	**47**	3,935	**63**	4,978		
16	4,662	**32**	3,311	**48**	4,047	**64**	4,994		

Table A2. Data of the second experiment of the dust concentration measurements for Soma coal with 0-2.5 micrometers particle size range and 1445,1 m/min tip speed of saw (T = Time interval; C = Average dust concentration)

T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)
1	0,764	**27**	2,458	**53**	2,522	**79**	3,485	**105**	5,861	**131**	11,242
2	3,152	**28**	2,711	**54**	2,809	**80**	3,673	**106**	4,282	**132**	9,671
3	5,353	**29**	2,536	**55**	2,959	**81**	3,724	**107**	3,774	**133**	9,996
4	5,846	**30**	3,015	**56**	2,303	**82**	4,147	**108**	4,074	**134**	10,690
5	5,206	**31**	2,604	**57**	2,480	**83**	4,051	**109**	5,447	**135**	9,133
6	4,396	**32**	2,256	**58**	2,297	**84**	3,863	**110**	7,609	**136**	8,163
7	4,283	**33**	2,211	**59**	2,129	**85**	3,501	**111**	12,576	**137**	8,503
8	4,929	**34**	2,533	**60**	2,196	**86**	3,600	**112**	13,977	**138**	7,888
9	4,942	**35**	2,972	**61**	2,943	**87**	3,322	**113**	12,580	**139**	6,779
10	4,493	**36**	3,033	**62**	3,742	**88**	2,964	**114**	11,420	**140**	7,223
11	4,029	**37**	2,727	**63**	3,553	**89**	3,230	**115**	12,576	**141**	7,915
12	4,216	**38**	2,561	**64**	3,581	**90**	3,731	**116**	14,233	**142**	7,152
13	3,792	**39**	2,591	**65**	3,120	**91**	4,162	**117**	13,177	**143**	6,630
14	4,110	**40**	2,492	**66**	3,035	**92**	4,881	**118**	13,238	**144**	6,552
15	3,925	**41**	2,253	**67**	3,109	**93**	4,791	**119**	12,091	**145**	6,561
16	3,363	**42**	2,407	**68**	2,920	**94**	4,481	**120**	11,010	**146**	5,968
17	3,041	**43**	2,416	**69**	3,412	**95**	4,080	**121**	9,855	**147**	5,932
18	3,075	**44**	2,544	**70**	4,013	**96**	4,128	**122**	9,008	**148**	5,752
19	3,512	**45**	2,589	**71**	3,875	**97**	3,930	**123**	8,738	**149**	5,645
20	4,096	**46**	2,551	**72**	3,566	**98**	3,622	**124**	11,050	**150**	5,618
21	3,390	**47**	2,724	**73**	3,321	**99**	3,774	**125**	11,969	**151**	5,875
22	3,560	**48**	2,606	**74**	3,975	**100**	3,468	**126**	12,292		
23	3,103	**49**	2,337	**75**	4,559	**101**	3,593	**127**	10,445	**Average : 5,120**	
24	2,583	**50**	2,017	**76**	4,361	**102**	4,700	**128**	9,996		
25	2,934	**51**	2,210	**77**	3,820	**103**	5,464	**129**	10,932		
26	2,700	**52**	2,418	**78**	3,719	**104**	4,522	**130**	12,414		

Table A3. Data of the first experiment of the dust concentration measurements for Soma coal with 0-5 micrometers particle size range and 1445,1 m/min tip speed of saw (T = Time interval; C = Average dust concentration)

T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)	T (second)	C (mg/m^3)
1	0,842	**27**	4,385	**53**	8,114	**79**	23,455
2	2,953	**28**	5,315	**54**	7,326	**80**	27,154
3	3,544	**29**	5,224	**55**	5,371	**81**	27,637
4	3,788	**30**	4,613	**56**	6,025	**82**	24,538
5	3,568	**31**	5,130	**57**	7,213	**83**	18,464
6	3,336	**32**	4,560	**58**	8,802	**84**	15,207
7	3,105	**33**	4,239	**59**	9,172	**85**	18,494
8	2,961	**34**	3,563	**60**	7,768	**86**	19,399
9	3,125	**35**	3,103	**61**	8,172	**87**	21,571
10	2,708	**36**	3,090	**62**	9,404	**88**	21,386
11	2,467	**37**	3,110	**63**	10,789	**89**	21,386
12	2,427	**38**	2,051	**64**	10,334	**90**	20,646
13	2,536	**39**	1,906	**65**	9,743	**91**	23,722
14	2,974	**40**	1,881	**66**	10,152	**92**	23,722
15	3,151	**41**	2,271	**67**	14,064	**93**	32,092
16	3,415	**42**	2,546	**68**	14,148	**94**	36,215
17	3,800	**43**	3,465	**69**	12,102	**95**	35,001
18	2,168	**44**	4,039	**70**	12,428	**96**	33,445
19	1,735	**45**	4,080	**71**	16,907	**97**	27,378
20	1,944	**46**	3,970	**72**	19,068	**98**	22,163
21	2,952	**47**	3,406	**73**	14,426	**99**	17,839
22	3,287	**48**	4,554	**74**	8,930	**100**	16,007
23	4,219	**49**	4,493	**75**	10,582	**101**	19,507
24	3,796	**50**	3,993	**76**	13,084	**102**	23,722
25	4,071	**51**	4,959	**77**	17,634	**Average : 10,266**	
26	3,628	**52**	9,299	**78**	23,455		

Table A4. Data of the second experiment of the dust concentration measurements for Soma coal with 0-5 micrometers particle size range and 1445,1 m/min tip speed of saw (T = Time interval; C = Average dust concentration)

T (second)	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**	**T (second)**	**C (mg/m^3)**
1	1,212	**27**	1,661	**53**	8,017
2	3,096	**28**	2,437	**54**	7,765
3	5,146	**29**	2,593	**55**	7,831
4	7,349	**30**	2,064	**56**	8,831
5	7,361	**31**	3,093	**57**	8,722
6	6,687	**32**	4,640	**58**	10,195
7	4,841	**33**	5,110	**59**	8,933
8	4,292	**34**	5,324	**60**	8,758
9	4,291	**35**	5,152	**61**	8,292
10	4,440	**36**	5,202	**62**	7,402
11	4,281	**37**	4,920	**63**	6,351
12	4,154	**38**	5,026	**64**	6,870
13	4,415	**39**	4,121	**65**	9,596
14	4,064	**40**	4,134	**66**	12,641
15	4,160	**41**	4,995	**67**	18,310
16	3,990	**42**	8,136	**68**	20,380
17	3,828	**43**	9,553	**69**	20,380
18	3,945	**44**	10,498	**70**	27,753
19	4,279	**45**	10,221	**71**	18,826
20	4,652	**46**	9,517	**72**	19,869
21	4,557	**47**	9,714	**73**	21,495
22	4,149	**48**	7,530	**74**	20,975
23	2,813	**49**	8,152	**75**	23,533
24	3,487	**50**	9,023	**76**	22,844
25	2,867	**51**	8,700	**Average : 7,969**	
26	1,954	**52**	9,262		

APPENDIX B

X-RAY DIFFRACTION PATTERNS OF THE COAL SAMPLES

X-ray diffraction pattern of the six coal samples are given in Table B.1-B.6.

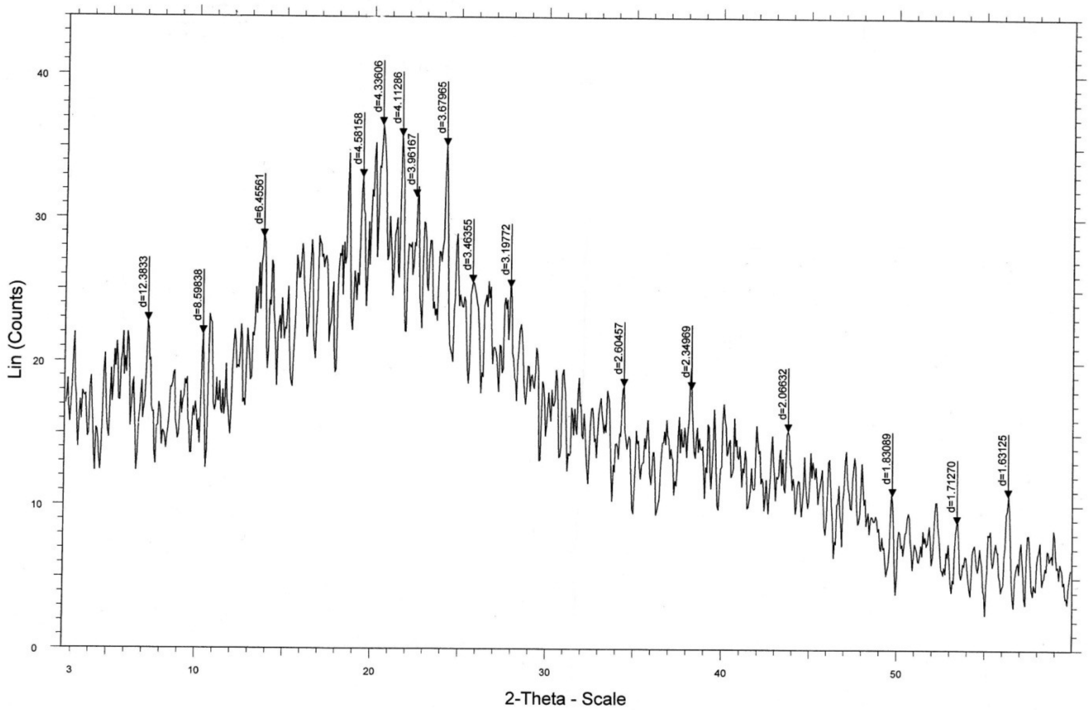

Figure B.1. X-ray diffraction pattern of Bursa coal sample

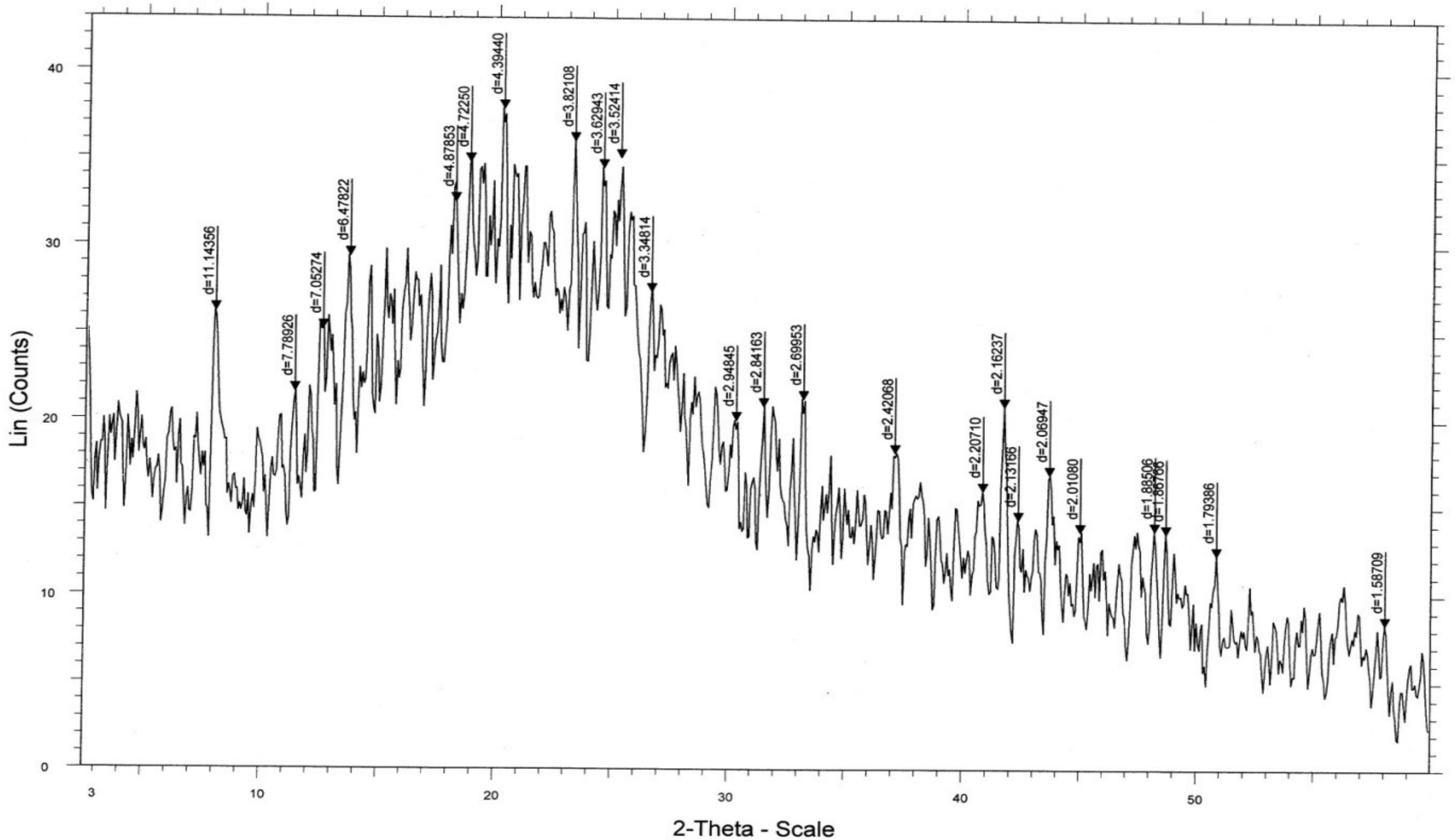

Figure B.2. X-ray diffraction pattern of Soma coal sample

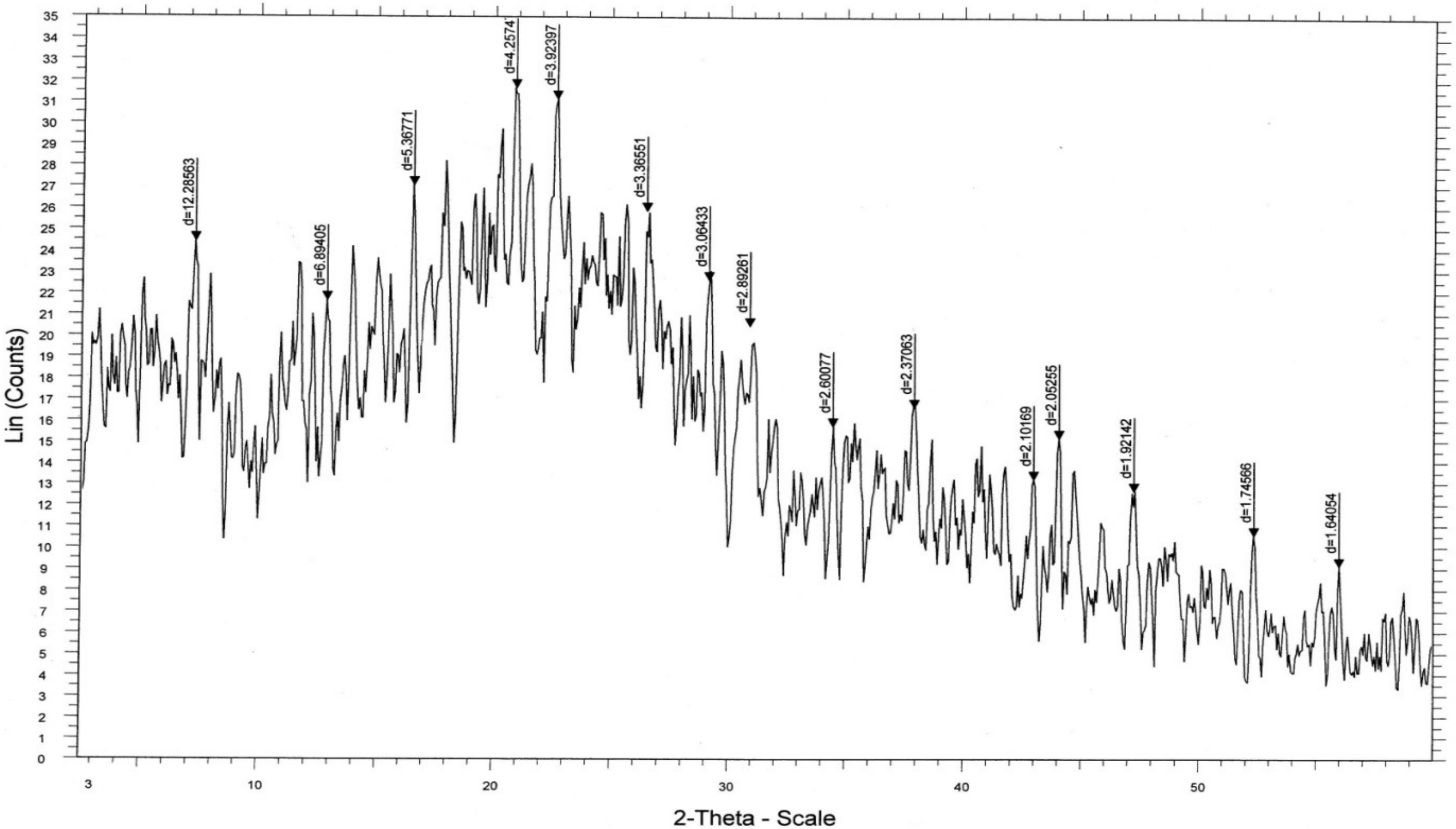

Figure B.3. X-ray diffraction pattern of Seyitömer coal sample

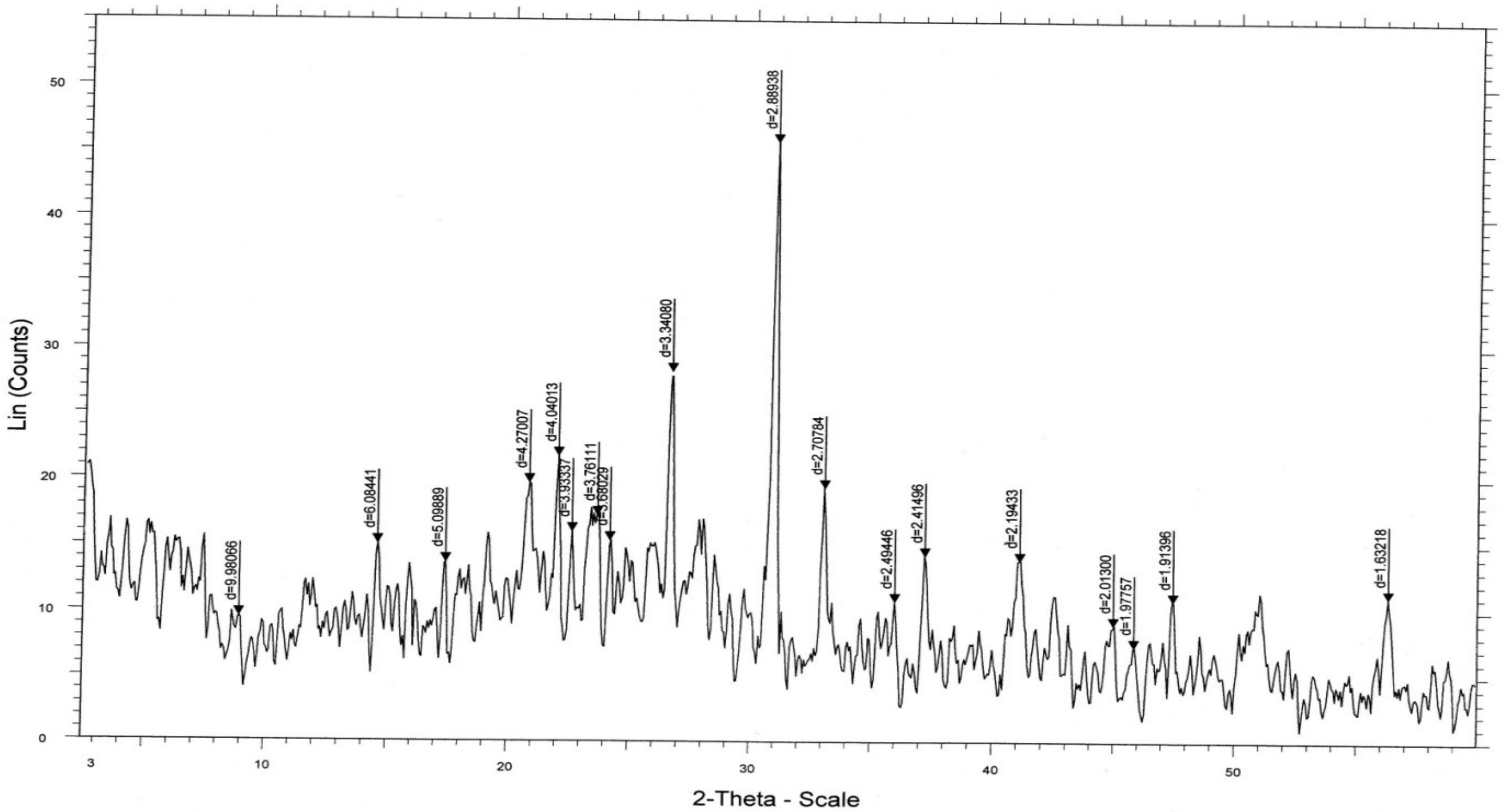

Figure B.4. X-ray diffraction pattern of Beypazarı upper coal seam sample

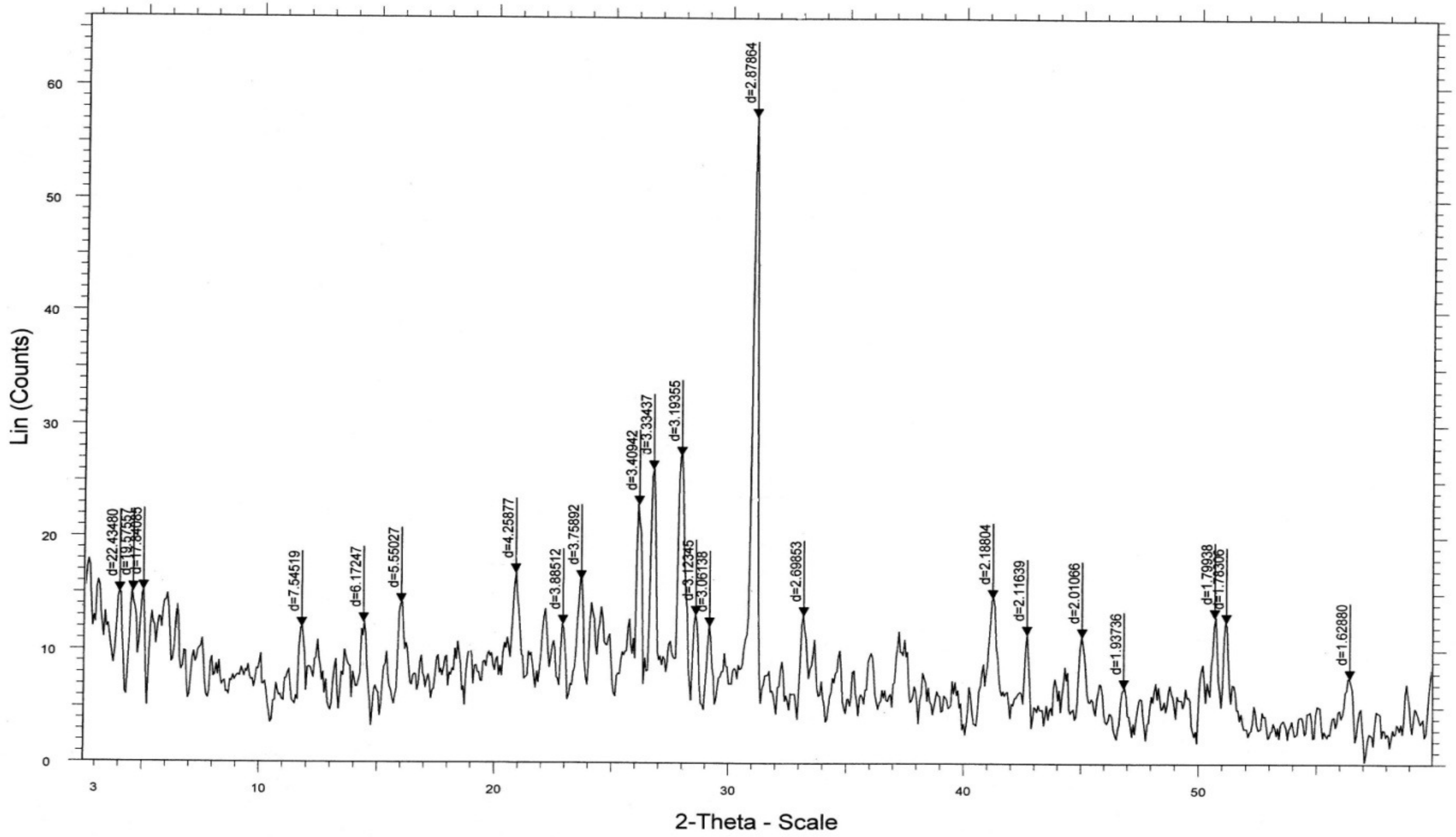

Figure B.5. X-ray diffraction pattern of Beypazarı lower coal seam sample

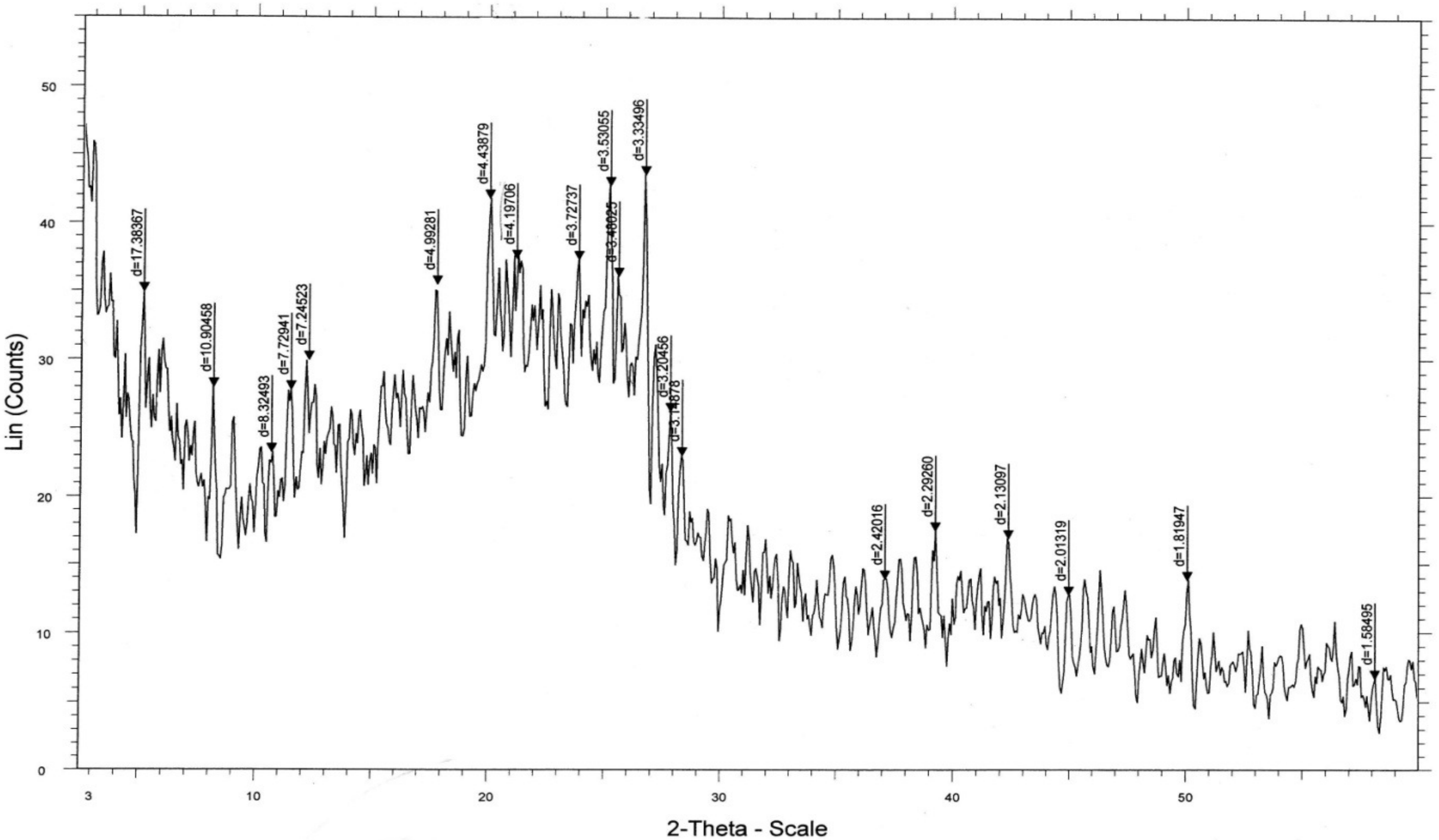

Figure B.6. X-ray diffraction pattern of Tunçbilek coal sample

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Karakaş, A., Güyagüler, T., "Orta Anadolu Çayırhan Kömür İşletmesinde Toz Koşulları Üzerine Bir Araştırma", Türkiye 13.Kömür Kongresi Bildiriler Kitabı, Zonguldak, Türkiye, (2002).

Güyagüler, T., Karakaş, A., "An investigation of Dust Control in the Middle Anatolian Lignite Mine, Turkey", North American Ninth U.S. Mine Ventilation Symposium, Kingston, Ontario, Canada, (2002).

Karakaş, A., Güyagüler, T., "Dust Sources and Preventing Methods in Longwall Coal Mines", Eighth Conference on Environment and Mineral Processing, VSB Technical University of Ostrava, (2003).

HOBBIES

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