Chapter 2

Literature Review

2.1 Introduction

The growth of any nation is highly dependent on its quantity of energy resources. For a developing country like India, coal is still a basic fuel for fulfilment of its energy demands. Coal is the most abundant fossil fuel resource present in India. Indeed, there has been a historical link between coal and economical progress of the nation. Coal is the main source of energy for domestic purpose as well as industrial applications like electricity generation, steel plants, cement and other industries.

Mines are designed to work the coal seams either through opencast or through underground methods depending on the technical feasibility and economic viability. Coal India Limited, the largest coal producing company of the world, has 369 mines (as on 31st Dec, 2018) of which 174 are underground, 177 opencast, and 18 mixed type mines. The production of coal is 730 MT in 2018-19 compared to 675 MT in the previous year, which shows a growth of 8.1% [7].

Coal production trend from 2010 to 2019 is shown in Figure 2.1. Mechanized opencast mining (OCM) is presently the commonly adopted technology for extraction of thick seams at shallow depth. This is also important from conservation point of view since the percentage recovery by this technology is around 80% to 90%. Production of coal by Coal India Limited

(CIL) is 607 MT for period of 2018-19. Production of coal through opencast mining (OCM) reaches up to 95% (576 MT) of the total production whereas only 5% (30 MT) is through underground mining (UGM) in 2018-19 (Table 2.1).

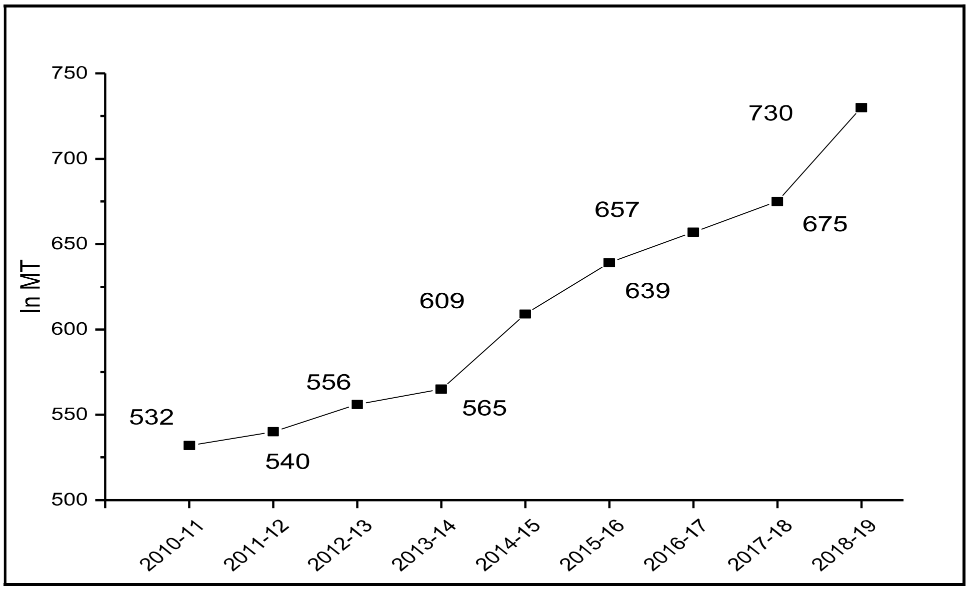

Figure 2.1 Coal production trend in India (2010-2019)

Table 2.1 Production of coal (in MT) through OCM and UGM methods by CIL

Year	Opencast Mining Method		Underground Mining Method	
	Production (MT)	% of Total production	Production (MT)	% of Total production
2013	414	91.7	38	8.4
2014	426	92.2	36	7.9
2015	459	92.9	35	7.1
2016	505	93.7	34	6.3
2017	523	94.3	31	5.7
2018	537	94.8	31	5.4
2019	576	95	31	5

From Table 2.1, it is apparent that opencast mining method has an edge over the underground mining method. Through OCM, not only the production rate increases, but also the safety of mine workers is enhanced. But, on the other hand, tremendous amount of dust is generated in OCM as compared to UGM [8].

Surface mining technology is employed in which the coal/ore lies at shallow depth of earth crust and that can be extracted by removing the covering layers of soil and rock. Almost all operations in opencast mining are exposed to the atmosphere. Several activities simultaneously go on, from where dust is emitted either due to machinery movement over haul roads and transport roads or operations like drilling, blasting, overburden/coal removal, overburden/coal loading/unloading, coal handling, crusher plant, workshop, stock yard, overburden dumps etc. [9].

Table 2.2 Removal of overburden from 2013 to 2019 in India

Year	**Overburden removal (million cubic meter)**
2013	747
2014	805
2015	886
2016	1149
2017	1156
2018	1178
2019	1162

In general, huge amount of overburden is to be removed to reach the coal seam. Table 2.2 shows the trend of overburden removal from 2013 to 2019 in India. Each current year removes more overburden from its previous year. Both mineral and overburden are transported through the haul roads to stock yard and dump site respectively. Hence, hauling is also recognized as the backbone of surface mining system. Out of all the major operations, vehicular traffic on haul road in opencast mines has been recognized as the most prolific source of fugitive dust emission [10].

Research article published by Reed and Organiscak (2007) suggests that the airborne dust emission of haul road which is composed of visible or invisible particulate matters, contributes approximately 70% to 97% of total dust emission [3]. Vehicle movement on haul road has been recognized as the most critical source of fugitive dust generation. According to Cowherd (1990), the contribution of dust generation through vehicular traffic on haul road is 80% of total dust emission in the mine [11].

Amponsah-Dacosta (1997) did an experiment by following US EPA guidelines to find out the suspended particulate matter (SPM) emission from New Vaal Colliery Opencast Coal Mine in Johannesburg of South Africa [12, 13]. He found that SPM emission from haul road is 92.2% of total dust emissions. Table 2.3 illustrates the percentage of dust generation from different operations in the coal mine. Overburden removal is next largest source of dust emission which contributes 2.5% of total dust generation followed by coal removal (2.1%), topsoil handling (1.9%), wind erosion (0.6%), coal handling (0.2%), blasting (0.2%), drilling (0.1%), and miscellaneous (0.2%).

Table 2.3 Percent contributions of SPM emission from various activities in South African mines

Operation	**PM_{10} emission (%)**
Haul roads	92.2
Overburden	2.5
Coal removal	2.1
Topsoil	1.9
Wind erosion	0.6
Coal handling	0.2
Blasting	0.2
Drilling	0.1
Miscellaneous	0.2

In the context of Indian scenario, Chaulya et al. (2011) reported that about 75% of total dust generation is due to the movement of vehicle on unpaved haul road, including up to 25% dust released due to loading and unloading operations [14].

A field study has been conducted by Central Mining and Research Institute to analyze the dust emission status from different activities of Indian coal mines [15]. It is found that haul road is the largest source of dust generation (80.20%). Second largest source of dust generation is screening plant contributing 8.1%. This is followed by overburden removal (2.8%), top soil handling (2.6%), coal extraction (2.2%), drilling and blasting (1.3%), coal stockpile or handling (1.1%), miscellaneous work (1.7%) (Figure 2.2).

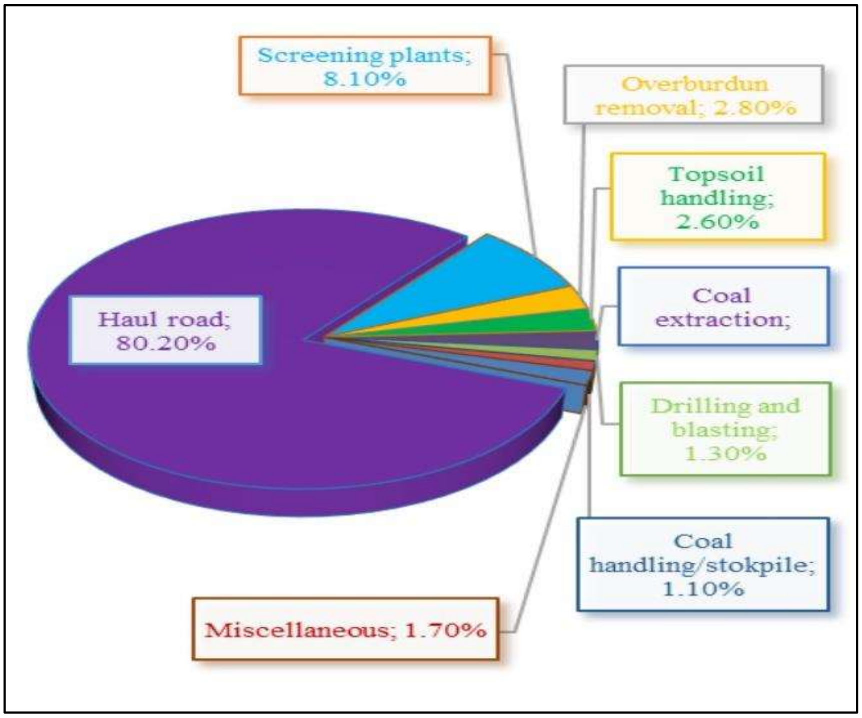

Figure 2.2 Generation of dust emissions (%) from a typical Indian opencast coal mine

In addition to dust emission, accidents are also major issues in haul roads as per the safety concern of mine workers. Many a times, accidents may convert into fatal one due to the deployment of heavy and large size equipment. The number of fatal accidents involving trucks is more compared to all other equipment related to mining operations. Simpson *et al.* (1996) observed that 74% of the accidents were associated with ore or overburden transfer by haul trucks and service vehicle operation in South African mines [16].

According to US Mine Safety and Health Administration (US-MSHA) reports, 633 mining fatalities occurred during 1995 to 2011 in the United State **(**Figure 2.3**)** [17]. Out of this 137 fatalities i.e. 21.6% of the casualties took place due to transportation by vehicle on haul road.

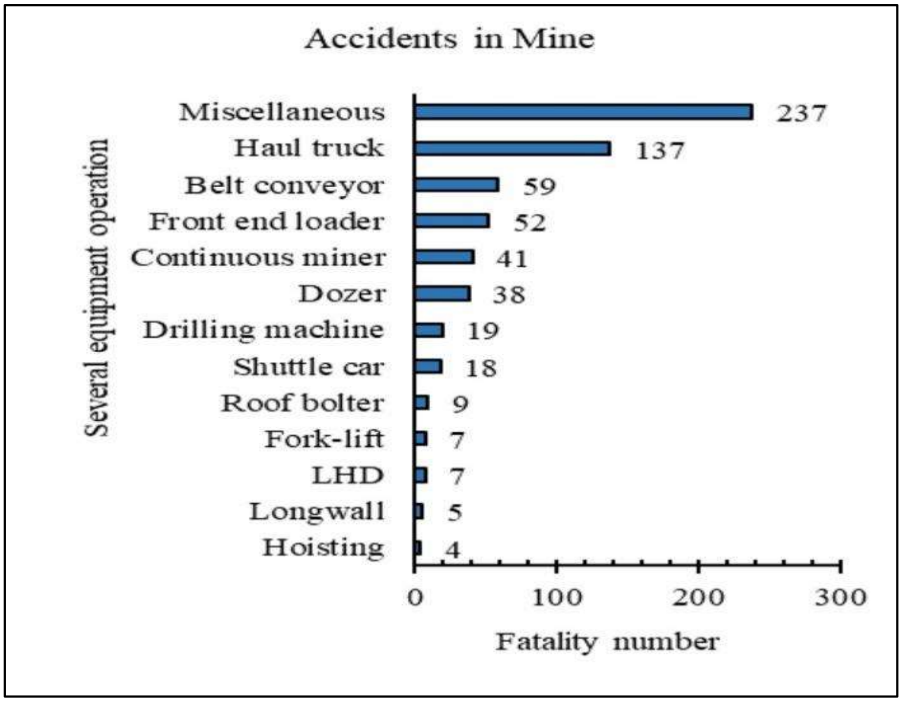

Figure 2.3 Equipment related fatalities number between 1995 to 2011 in USA

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2.2 Dust Generation in Haul Roads

Haul roads are basically classified into two categories based on the inclination: high grade and low grade [18]. High grade haul road surface is made by gravel or sandstone while low grade one is simply built on rough ground. Due to frequent maintenance required in low grade haul roads, overall cost of production increases by many folds. Again, haul roads are rarely made of high grade by using gravel or sandstone due to high cost of maintenance and construction as well as it is not likely to be a permanent structure. Therefore, in general, haul road is made of the parent soil material. All the vehicles like haul truck, excavator, loader and other heavy earth moving machines also run over the haul road.

The science behind the dust suspension in the air is that for any particle to become airborne, it must have an aerodynamic drag force larger than the sum of the particle weight and the inter particle forces [19]. Smaller particles will behave like gaseous molecules. They will be influenced by molecular forces due to very low weight, while larger particles will be affected by gravitational and inertial forces [20]. Rolling wheels of the vehicles induce heavy amount of force on the surface of roadbed material. Wheels impart a force to the surface that crushes the road material and pulverizes it. Loose materials may be ejected to the atmosphere by the turbulent vehicle wakes and also by the shearing force [21]. The large size suspended particles come down very quickly after passing of the vehicles.

The vast majority of dust particles created during breakage are not released into the air but stay attached to the surface of the broken material [22]. Wetting of this crushed material ensures that the dust particles stay attached to the broken material. As a result, addition of water to the dust particles can usually be counted on to reduce dust emission [23, 24]. More the moisture present, less the dust will be airborne.

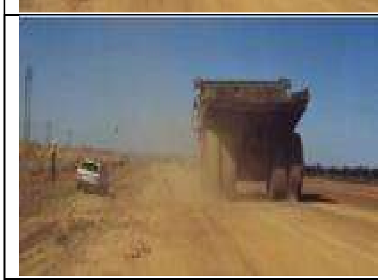
Various researchers have found that dust emission from unpaved road not only depends on the properties of haul road parent material but also on the various other factors like vehicle speed [21, 25], vehicle weight [26], traffic density [27], wind speed [28], soil density [29], soil moisture content capability [30], fine particles present in road [31], restraint capacity of the surface fines (compaction, cohesiveness, bonding and durability) [32], and atmospheric condition like wind speed, temperature and humidity [33, 34].

2.2.1 Estimating Dust Concentration Using Visual Method

South African researchers Thompson and Visser (2007) developed a method to identify the dust concentration levels of haul road based on the capability of human eye to detect contrast between an object and its surroundings [28]. The clarity of an object seen through a cloud of dust will be perceived differently from person to person, so visual monitoring is a very subjective measurement [35]. However, over a common range of airborne dust concentrations, a visual scale is good enough to provide a useful monitoring tool. They developed a useful visual scale for the field guide as presented in Table 2.5.

Table 2.5 helps to roughly estimate the PM_{10} content by visualizing dust cloud near the haul road while vehicles are running. Dust Intensity Factors (DIF) listed in the Dust Levels column represent the quantitative approximations of relative PM_{10} content of the dust cloud depicted in each photo. The relatively higher dust content of the Table 2.6 Degree 4 photo (DIF = 14) compared to the Degree 2 photo (DIF = 4) is simply 14 ÷ 4 = 3.5. In other words, the PM_{10} content of a Degree 4 dust cloud is quantified as being approximately 3.5 times higher than that of the Degree 2 dust cloud.

Table 2.4 Standard photos for visual estimation of dust concentration

Dust Reference Photos	**Degree of Dust (Cloud Opacity)**	**Dust Levels (µg/m^2 for PM_{10})**	**Severity**	**Qualitative Descriptions**
	Degree 1	< 3,500 Dust intensity Factor = 1	Slight	Minimal Dust.
	Degree 2	3,500–23,500 Dust Intensity Factor = 4	Between slight and warning	Dust visible only behind vehicle.

	Degree 3	23,500–45,000 Dust Intensity Factor = 10	Warning	Dust visible, driver discomfort zone, good visibility.
	Degree 4	45,000–57,500 Dust Intensity Factor = 14	Between warning and severe	Notable dust, visibility just acceptable, overtaking/ passing dangerous.
	Degree 5	> 57,500 Dust Intensity Factor = 16	Severe	Tremendous amount of dust, visibility very poor, overtaking/ passing not possible.

2.3 Nature and Characteristic of Haul Road Dust

A large quantity of dust is generated from the haul road. Coarse particles do not become airborne due to their high weight. But tiny particles, due to their low weight, have very high tendency to get uplifted from surface of road and remain suspended in the air for comparatively longer duration depending on their size. According to Williams et al. (2008), fine particles of size below 100 μm have tendency to remain suspended in the air [36]. Of late, many researches are engaged in carrying out experimentation to understand the science behind the emission of fugitive dust due to haul road transportation system in opencast mines.

Amponsah-Dacosta (1997) had estimated the emission of PM_{10} from all mining activities [12]. Table 2.5 demonstrates the percentage of dust generation from different operations in the coal mine. The highest PM_{10} emission is 93.3% from haul road. Topsoil handling is next largest source of dust emission which contributes 2.7% of total dust generation followed by overburden stripping (1.6%), wind erosion (0.9%), coal removal (0.8%), blasting (0.3%), drilling (0.1%), and miscellaneous operations (0.2%).

Table 2.5 PM_{10} emission from opencast coal mine in South Africa

Operation	**PM_{10} emission (%)**
Haul roads	93.3
Topsoil	2.7
Overburden	1.6
Wind erosion	0.9
Coal removal	0.8
Blasting	0.3
Drilling	0.1
Coal handling	0.1
Miscellaneous	0.2

A research report was published by Sinha and Banerjee (1997) on haul road of Noamundi Opencast Iron Ore Mine (NOIM), situated at West Singhbhum in the Indian state of Jharkhand [37]. They found that about 60% of total SPM was within 0-10 µm size range. The average particle size distribution of SPM and PM_{10} emanated from the haul road of NOIM is presented in Figure 2.4. The PM_{10} at 0.05-1.1 µm, 1.1-2.0 µm, 2.0-3.3 µm, 3.3-7 µm, and >7 µm size range were found to be 5%, 8%, 15%, 28%, and 44% respectively.

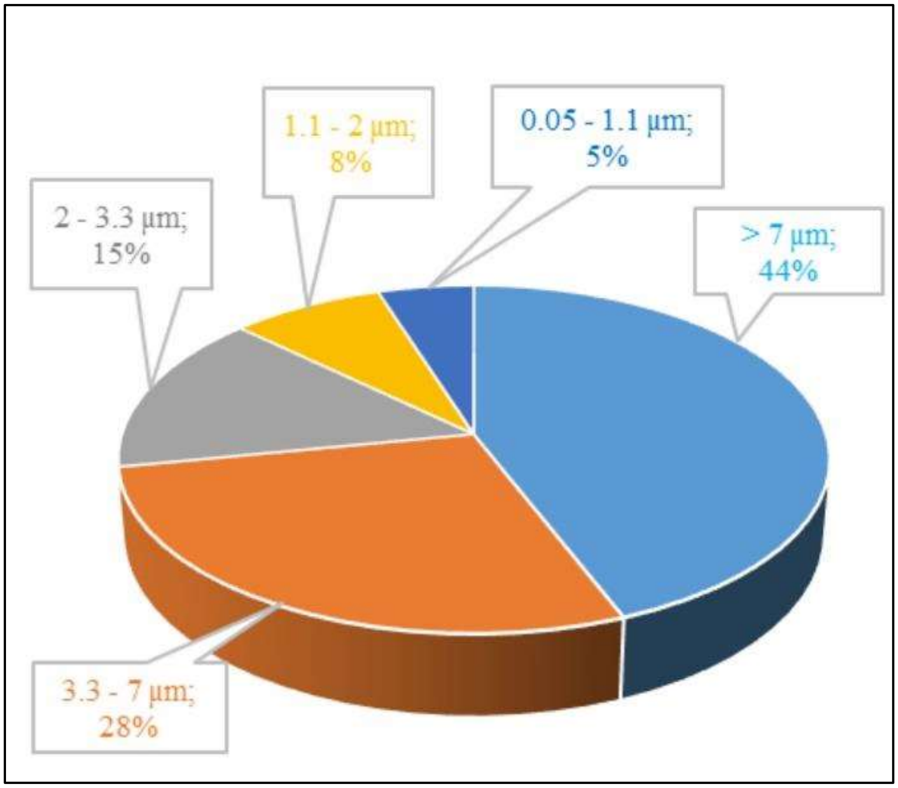


Figure 2.4 Size distribution of haul road dust from Noamundi Opencast Iron Ore Mine, India

Ghose (2002) carried out a field study in Block-II opencast coal mine in Jharia Coalfield of Dhanbad district, Jharkhand, India [38]. This area was the most polluted coalfield due to concentrated mining activities. SPM was collected during winter (January), summer (May-June), monsoon (August) and post-monsoon (October) periods. Table 2.6 summarizes the average particle size of SPM generated from haul road. 96.8% of SPM consisted of particle size below 60 µm.

Table 2.6 Weight percentage of SPM generated from haul road in Jharia Coalfield

Size range (μm)	**Percentage by weight**
0-2	5.9
2-5	5.3
5-10	12.1
10-20	26.2
20-40	36.0
40-60	11.3
>60	3.2

Another experimental study was conducted by Organiscak and Reed (2004) at two sites of USA: (i) a limestone quarry haul road, and (ii) a haul road at coal preparation plant. 20 ton and 50 ton haul trucks were running at the speed of 15.6 mph in limestone quarry haul road [39]. Haul road of coal preparation plant operated 50-60 ton road trucks travelling at an average speed of 15.9 mph. The particle size distribution of dust generated from haul trucks was calculated by cascade impactor sampler from both the sides of haul road. The average particle size distribution is shown in Figure 2.5. 85.5% of SPM generated due to haul trucks on haul road, consists of particle size more than 10 μm. Only 14.5% of the airborne dust consists of respirable fraction (i.e. less than 10 μm particle size), which affects the health of the operators and other mine workers. Though the larger size fraction of dust do not affect the lungs directly, they indirectly increases the safety threat of truck operators due to reducing the visibility.

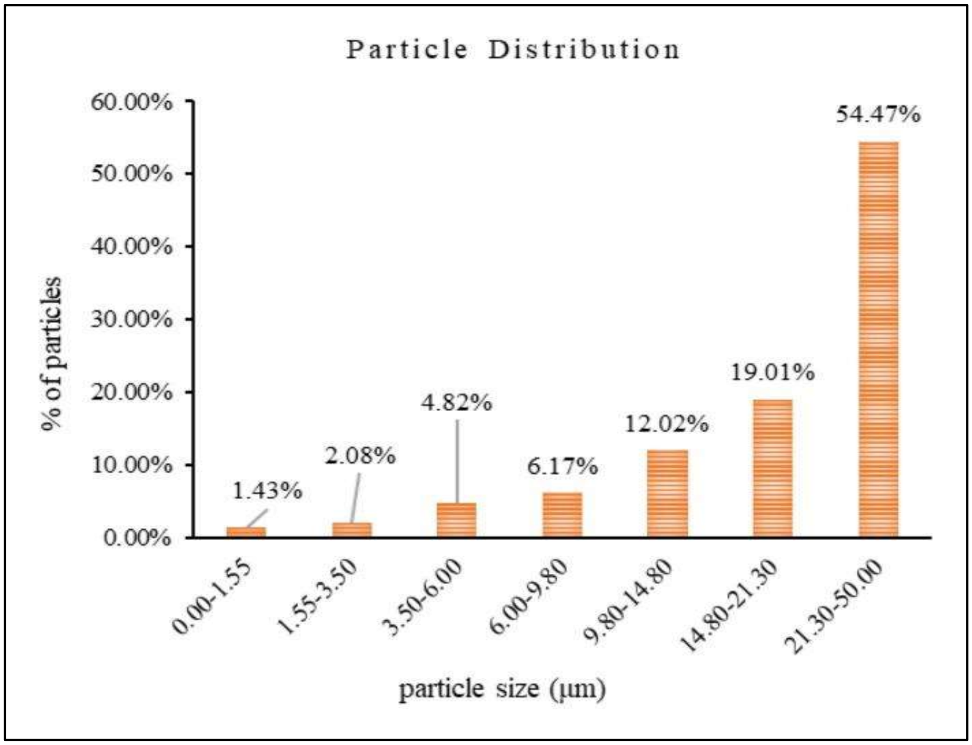


Figure 2.5 Size distribution of particulate matter generated from haul road in USA

2.4 Impact of Dust

It is apparent from the above section that wide range of dust particulate matters (PM) are generated from haul road of surface mining. A fraction of the generated dust, called SPM, remain suspended in the atmosphere. The SPM directly or indirectly cause harm to humans, other living organisms and natural environment [40]. Due to inhalation of dust in a high concentration, several diseases may occur in human body like non-fatal heart attacks, asthma, lung or heart disease, coughing, breathing problems, irregular heartbeat and other pneumoconiosis diseases. Various researches have worked on the occupational health exposure and pneumoconiosis due to dust inhalation as summarized in Table 2.7 [41-43]. Mainly, below 10 μm size particles have high predicated penetration capacity into the lung. On the other hand, particles above 10 μm size have the chance of inhaling by the human being but does not cause health problems because they are trapped in the nostrils or mouth and comes out along with cough. Environment protection agency (EPA) has been regulating particulate matter mainly in two size categories PM_{10} and $PM_{2.5}$ based on their impact on human health. PM of size 4-10 μm diameter are able to reach the throat region, and therefore, is known as thoracic PM. Below 4 μm size PM get deposited in the alveoli, and is called as Alveolic PM [44]. Fine particles of $PM_{1.0}$ and $PM_{2.5}$ are more likely to be inhaled deep into the lungs. Alveolic PM has more potential to cause adverse health impacts, prominent of them being the lung dysfunction and lung infection. Table 2.8 elaborates the chemical composition of PM and its impact on human health.

Table 2.7 Research report on various diseases due to dust inhalation

Disease	**Reference**
Asthma	(Pless-Mulloli *et al*., 2000) [45]
Black Lung Disease	(Finkelman *et al*., 2002) [46]
Cardiovascular	(Chen *et al*., 1990; Hendryx 2009) [47,48]
Mesothelioma	(Shah 1998) [49]
Parkinson's Disease	(Buzea *et al.,* 2007) [50]
Alzheimer's Disease	(Quintana *et al.,* 2006) [51]

Table 2.8 Chemical composition of PM and its impact on health

Chemical constituent of PM	**Name of Disease**	**Health Hazard**	**Reference**
Asbestos	Asbestosis	Cause lung cancer, mesothelioma and pulmonary damage.	(Donoghue, 2004) [52]
Silica	Silicosis	Cause obstructive airway, lung cancer, emphysema, etiology, immune and lymphnode fibrosis.	(Donoghue, 2004) [52]
Copper	Copperied us	Cause Wilson's disease.	(Quintana *et al.* 2006) [51]
Iron	Siderosis	Cause Alzheimer's disease and Parkinson's disease.	(Chen *et al.,* 1990; Quintana *et al.,* 2006) [47,51]
Mica	Pneumoco niosis	Damage respiratory system.	(Heimann et al. 1953) [53]
Beryllium	Berylliosis	Cause chronic and acute lung diseases and lung cancer.	(Middleton and Kowalski, 2010) [54]

Dust not only has severe impact on human being, it also inflicts health problems in animals and plants, and negative effects on infrastructure. Animal's exposure to dust has more or less similar effect as in human health. Respiratory system may start improper functioning. Rate of growth of plant reduces or may stop when it is exposed in regular and high dust concentration. There is high chance to disease attack to plants, their stomata and other holes get chocked which affect its respiration system. Vegetables, fruits and cereals from these plants contain toxins. Elements existing in the coal dust start interacting with the constituents of the host surface materials, which may increase the rate of weathering leading to its weakening.

2.5 Why Dust Control is Important

Loss of fine particles from driving surfaces produces mainly three significant problems:

1. High level of dust reduces the visibility which inflicts to reduce the speed of vehicles and also to increase accident rate.
2. High concentration of dust causes pneumoconiosis. Not only human health is affected by dust, but also animals, crops and forest are affected.
3. Fine particles act as a binder. Without it, degradation of the road surface takes place. Pothole, corrugation and rutting are all evidences of loss of fine particles, ultimately producing uncomfortable driving situations, thereby increasing the accident risk.

These fine particles can be held in the atmosphere not only for hours – even for a few days. They can be transported miles away from their source of generation. Therefore, each passage of a vehicle can enhance additional fine particles to the atmosphere. This calls for suppressing the dust from getting generated through implementation of a proper dust management plan.

2.6 Dust Control Methodology

The methodology for reduction of fugitive dust emission from haul road generally falls into three categories: (i) administrative method, (ii) mechanical method, and (iii) chemical method, as briefly discussed here.

2.6.1 Administrative method

Under this category, no modification is done in the design of haul road or no dust suppressant is used. Dust emission can be reduced by:

1. Limiting the speed of vehicles.
2. Limiting the loading capacity of vehicles.
3. Limiting the intensity of vehicle movements per hour or per shift.

Recently published research report of McHattie (2015) claimed that by dropping the vehicle speed from 30 mph to 15 mph, the emission of PM_{10} could be reduced from 80% to 30% from unpaved roads [55]. The findings of another report, Thompson and Visser (2000), is presented in Table 2.9 [20].

Table 2.9 Dust reduction by reducing vehicle speed

Vehicle Speed	Dust Reduction (%)
Reduction from 75 km/h to 50 km/h	40 to 75
Reduction from 65 km/h to 30 km/h	50 to 85

The main limitation of this method is that it reduces or slows down the production rate.

2.6.2 Mechanical method

Mechanical method of dust control focuses to improve the surface material of the haul road and its design. Normally, haul roads are made of small stone or gravel or small chip, or parent soil or parent rock, or combination of these materials. The quality of material and its size also play the crucial role to sustain the load of vehicle. According to the Liu and Lu (2015), haul road made of higher grade can reduce road maintenance cost by 65% while speed of hauling vehicle can increase by 50% [56].

This is the most effective way of dust reduction. In this method a bound pavement surface or sealing of the haul road surface is provided by using concrete. Up to 95% of dust generation can be reduced by bound paving [20].

The limitation of this method is high cost of construction and its maintenance. As the orientation of haul roads changes frequently in mines, for most of the cases it is not a feasible solution.

2.6.3 Watering Method

Spraying of water is a traditional way of reducing dust generation from unpaved surface of haul road. Water is the most cost effective as well easy-to-apply as a short-term solution for dust control [57].

Axetell & Cowherd (1984) carried out an experiment on haul road of coal mine in the USA. They found that water spray at a rate of 0.05 gal/yd^2 can reduce particulate emission by 60-70% immediately after 1 hour of water spray [58].

Effectiveness of water has been found to be between 40% to 85% in controlling dust emission from unpaved road, but highly dependent on site and climate condition [59-61].

Water has high surface tension due to which it cannot effectively keep wet the haul road surface particles for a long duration. Other researchers, such as Thompson and Visser (2007), found that instead of cohering to one another, the molecules of water spread out over time, which increases surface tension and thus increases the evaporation rate [28]. Due to high surface tension of water, the bonding between water molecules and surface materials will show less resistance which also provides low intensity to bind small particles together as well as with large particles. Once water dries up, the dust starts pulverising and uplifting from surface of road, that lead to formation of airborne dust particulates.

It requires enormous quantity of water in the dust management of haul roads in a mine. It is true that water spraying is the cheapest and easiest tool available for the treatment of dust reduction. But at many places, present situation is changing due to vital transformation of socio-economic scenario at every level. Therefore, investigation on effectiveness of other chemical dust suppressants are continuously going on.

The main problem faced while using water as a dust suppressant is that it evaporates very rapidly. Also, in the summer season, water is a scarce commodity near the mining area.

2.6.4 Chemical method

In place of improving the road surface material or reducing the vehicle speed, it is preferred to use some chemical dust suppressants like lingo-sulphonates, petroleum products etc. It will give better results in controlling dust emission in comparison to the above two methods.

The science behind it is that the tiny particles of road surface remain bounded and stick firmly with other particles in the road. Some dust suppressants like salts, polymers, foaming agent etc. work on the theory that spraying of these agents on haul road increases the moisture holding duration in comparison to water. In humid area, salts like calcium chloride and magnesium chloride work very well to control the dust emission due to absorbing of moisture from the atmosphere.

2.7 Chemical Dust Suppressants

While focusing to control dust emission from haul road, attention is to be given to achieve it without affecting the production rate as well as its cost. Chemical dust suppressants possess high potential to control dust generation at the source itself [62, 63]. When water or chemical solution is applied to an aggregate material, it binds the suspendable particulates to larger particles. Some of the methods are described below.

2.7.1 Water attracting salt

Water attracting chemicals are also used as dust suppressants for unpaved roads. Calcium chloride and magnesium chloride have hydroscopic property which attract moisture from the surrounding and help to keep binding the fine particles. One report is published by Jones (1996), regarding calcium chloride performance in which it indicates that calcium chloride works very well on haul road and also reduce the formation of corrugation and raveling [64]. Both the chemicals also have property to resist evaporation, therefore single application of it will work for long period if traffic is at moderate rate. There are two ways of application process. Either it is directly applied to surface with spray system or mixed with haul road dust during gravelling operation.

It is observed that chlorides have corrosive property. More wearing and tearing happen with vehicles, and also the environment is affected. Nearby plantation is directly affected due to adverse impact on fresh water availability. Magnesium chloride can irritate skin tissue with direct contact. High concentration of salts will affect plant growth and increase the risk of rusting of the metallic parts of motor vehicles [65].

2.7.2 Ligno-sulphonates

Ligno-sulphonates are waste products from the sulphite pulping process commonly used in the pulp and paper industries. It has the property like glue that binds the road particles together which directly reduces the generation of dust from haul road. A report of Jones (1996) concludes that Ligno-sulphonates have shown to be extremely effective in controlling dust of haul road, and at the same time it improves driving surface [65]. It is applied directly onto the road surface by a spray system or mixed into the road surface material during gravelling operation.

Plessis (2016) performed a comparative field study with lingo-sulphonate dust palliative and water-only in haul road [66]. It was found that at least 6 times water-only application per day is required to keep dust emissions at a safe and acceptable level on haul roads. Same status can be achieved by applying lingo-sulphonate with 3 times only. In other words, reduction in the frequency of application is at least 50%. And dust fallout decreases by 53.8%.

But, there is no mention of the concentration or amount of lingo-sulphonate application on haulage road to achieve the above performance.

2.7.3 Bitumen emulsions

Bituminous products are generally engineering products or by-products of natural petroleum extraction process. They act as emulsion and have the ability to contain dust. Their main advantage is to stop penetration of fluid passing through haul roads. It is reported by USBM (1987) that dust control efficiency can go up to 70% for the period of 21 days after application. They consist of stable emulsions of petroleum residuals, solvent extracts, and acid sludge, due to which they generate toxicity, and thereby, cause harm to the surrounding [67].

2.8 Polymers as Dust Suppressant

Polymers include acrylics, polysaccharides, vinyls, polyacrylamide and polyacrylamide-grafted-polysaccharides which are chemical additives for dust suppression. They are mixed with water to form a diluted solution and then sprayed to the road surface topically [68]. These additives bind surface soil particles together and form a semi rigid film on the road surface. They function by agglomerating fine particles, thereby forming a crust that is resistant to disintegration. Polymer solutions are directly applied on to the road by a spraying system. They are said to be very effective in sandy soils as well as in dry climates. In general, polymers are suitable for a large range of climate condition with minor variation in dilutions and application rates [63].

Polymers like acrylics and saccharides are considered as non-toxic, less reactive with other materials and environmental-friendly when used within permissible limits. The advantages of polymers are that they do no not suffer embrittlement, leaching nor UV degradation, and have good adhesive properties, making them potentially successful as dust suppressants [69]. Polymer as a dust suppressant has been used from almost starting of the invention related to haul road dust control program. Some of the past works related to dust suppression with the application of polymers are summarized below.

Omane et al. (2018), had performed an experiment to control the fugitive dust emission from haul road by using water, salt, chloride-free agent, polymer and molasses as dust suppressants of varying concentration (2-10%) at three different temperatures 35 °C, 15 °C and -19 °C [70]. The polymer solution was applied on haul soil during road construction at a wind speed of 65 m/s, and readings were recorded up to 72 h. Experimental results showed that at initial stage with 2% polymer concentration the average dust retention was 99.04%, and it raised to 99.70% at 10% concentration after 72 h.

Zhang et al. (2018), used hybrid guar gum mixed with wetting agent to improve its conglomeration effect as well as water retention capacity of the coal powder, giving rise to an enhanced dust suppression performance [4]. Modified guar gum has been tested with different concentration in the range of 0.2% to 3%. It was found that 0.8% concentration solution applied on coal dust sample had sustained a pressure of 29 KPa which was higher than at other concentrations. The experimental results indicate that the novel modified guar gum dust suppressant has boost cementing action, water retention, degradability and anti-compression characteristics, which will provide significant environmental and economic benefits to the dust control strategy.

Another research of Reed and Organisak (2007), conducted in a field study to measure dust emission from haul tracks in coal preparation plant in USA mine [3]. Emission of fugitive dust from haul road was controlled by spraying of water. From the result, it was concluded that control efficiency of total suspended particles from haul road had increased by 74%, when application rate of watering was 2.08 L/m^2 for 3 to 4 hours. Again, control efficiency had increased by 95% for total suspended particle (TSP) when watering rate was 0.59 L/m^2 after each half an hour.

Thompson and Visser (2003) also explored many aspects of controlling the dust emission from haul road of South African mines [71]. The real time field study was conducted with different dust suppressants such as water, hydroscopic salts, lingo-sulphonates, petroleum emulsions, polymer emulsions and tar bitumen emulsions. Through this study they could observe that the application of the palliatives depends on several parameters, such as, climate conditions, wearing course material limitation, self-repairable and tendency to leach out.

Bolander and Yamada (1999), had published a report, in which they described the expected environmental impacts including the limitations of application of various dust suppressants [63]. Table 2.10 presents a comparative study of different dust suppressants commonly available for controlling of fugitive dust emissions.

Table 2.10 Comparative study of different dust suppressants

Dust suppressant category	**Attributes**	**Limitations**	**Environmental impacts**
Water	1) Normally, readily available, easily applicable.	1) Evaporates rapidly.	1) No environmental impact.

	2) Agglomerates surface particles.	2) Short-term effectiveness.	
Calcium chloride Or Magnesium chloride	1) Water spray application. 2) Increases surface tension of water film between particles. 3) Helping to slow evaporation.	1) High humidity environment required. 2) Effectiveness destroyed by rain.	1) Corrosive to vehicles. 2) Adverse impact on water, plant and environment.
Ligno-sulphonates	1) Water spray application. 2) Binds surface particles together. 3) Increases strength of road material resistant to load stress.	1) Surface binding reduced or destroyed by heavy rain. 2) Become slippery when wet.	1) No impact on water quality or plant life. 2) Biodegradable
Bitumen emulsions	1) Water cart application. 2) Binds surface particles.	1) Surface slipperiness.	1) Potentially harmful to environment.
Synthetic polymers	1) Water cart application. 2) Binds surface particles 3) Retain effectiveness for long duration.	1) Difficult to maintain hard surface.	1) May or may not any impact on environment, (dependence on polymer properties). 2) Biodegradable or not.
Enzymes	1) Organic strengthening of road surface.	1).Needs some days of no traffic. 2).Effectiveness destroyed by heavy rain.	1) No impact on environment.

2.9 Research Gap

It is thus apparent from the past studies that fugitive dust emission is an environmental and operational problem at haul roads of surface mines. Advanced level of research in the field of dust control from haulage roads has not been carried out to the same extent as dust control from most industrial sources including other mining operations. Application of water is the most common and popular method used to control dust emissions. Water is often neither a long-lasting nor a cost-effective solution. At many places, it is a scarce commodity especially in summer seasons demanding it to be reserved. Therefore, there is an express need to develop some alternative dust suppressant chemicals which is more effective than water-alone system. At the same time, it would help to conserve the precious water for the present as well as future generations. Many possible chemical dust suppressants including some polymers can directly or indirectly cause harm to the environment. Previous published research articles disclosed little information regarding their application methodology. Detailed discussion was also not presented as to why the chemical suppressants worked better.

Therefore, in this study an emphasis has been given to develop water-soluble polymers which are environment-friendly. Also detail analysis has been presented under what conditions they work better and why.

2.10 Introduction on Polymers

Polymers are a very important class of materials, without which day-to-day life seems to be very difficult. They are all around us in everyday use – rubber, plastic, resins, adhesives, etc.

Application of polymers have gradually increased and reached up to nanotechnology due to its compatibility and economic viability [72].

Polymers are classified on the basis of their (i) origin – natural, semi-synthesized, synthesized; (ii) line structure – linear, branched, cross-linked; (iii) chain structure – hetro, homo; and (iv) polarity – polar, non-polar. The polymers, found in nature as raw materials, are called natural polymer; they are also known as biopolymers. Example of such polymers are: starch, cellulose, proteins, natural rubber, natural silk, etc. The polymer, which is synthesized in the laboratory is known as synthetic polymer, also called as man-made polymer. Some examples of such polymers are: polyethylene, polyvinyl alcohol, polyacrylamide, nylon etc.

2.11 Initiator for Polymerization

Initiators are often used in chain-growth polymerization such as free radical polymerization to regulate initiation by heat or light. Initiator is a compound, which can have organic or inorganic origin and its characteristic is to generate free radicals by a hemolytic cleavage of covalent bonds at its dissociation temperature. For ceric ammonium nitrate [$Ce(NH_4)_2(NO_3)_6$], the dissociation temperature is 60 ^oC.

2.11.1 Ceric Ammonium Nitrate

The initiator used for free radical polymerization (FRP) is ceric ammonium nitrate (CAN). CAN is an inorganic compound with the formula $(NH_4)_2 Ce (NO_3)_6$ (Figure 2.6). This orangered, water-soluble cerium salt is a specialized oxidizing agent in organic synthesis and a standard oxidant in quantitative analysis. In this research work, CAN has been used as the initiator for all the polymerization processes.

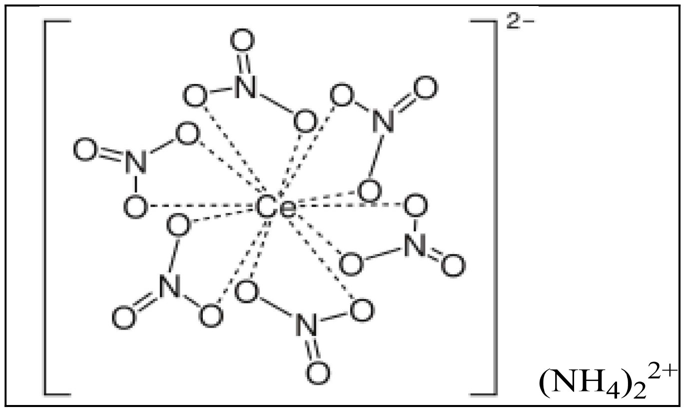


Figure 2.6 Structure of ceric ammonium nitrate (CAN) initiator

2.12 Polymerization Techniques

In general, there are mainly two types of polymerization techniques:

1. *Addition Polymerization*: When molecules having double bonds and just add on to form the polymer, the process is known as addition polymerization.
2. *Condensation Polymerization:* When molecules having more than one functional groups undergo some condensation losing small molecules in forming the polymer, the process is called condensation polymerization.

There are several sub-categories in addition polymerization process. Out of these, free radical process (FRP) method is very popular, and has been followed for synthesis of the polymers in the laboratory.

2.12.1 Free radical polymerization mechanism

In free radical polymerization technique a polymer is formed by the successive addition of free radical building blocks. Free radicals can be formed via a number of different mechanisms usually involving separate initiator molecules.

It is a type of chain growth polymerization. It is a process of polymer synthesis in which polymer grows by sequential addition of the monomer units. Free radical propagates at double bond of monomer units by successive breaking of the monomer double bond. Free radical polymerization is a key synthesis route for obtaining a wide variety of different polymers and material composites.

Advantages of free radical polymerization:

- Compatible with many monomers.
- Versatile with regard to reaction condition.
- Widely applied in industry for the above reasons.

Limitation of the free radical polymerization:

Due to diffusion-controlled termination reactions between the growing radicals, there is only a little scope for controlling over the molar mass distribution of the synthesized polymer.

2.13 Graft Co-Polymers

Graft co-polymerization is a method to impart a variety of functional units to a polymer. Graft polymers are copolymers with a linear backbone of one composite and randomly distributed branches of another composite. Although the side chains are structurally distinct from the main chain, the individual grafted chains may be homo-polymers or copolymers (Figure 2.7 & 2.8). Graft polymers have been synthesized for many decades and are especially used as impact resistant materials, thermoplastic elastomers, compatibilizers, or emulsifiers.

In this study, acrylamide monomers are grafted over the amylopectin and guar gum backbone. Here, amylopectin and guar gum behave as the main chain or backbone, whereas polyacrylamide chains are added as the branches on it.

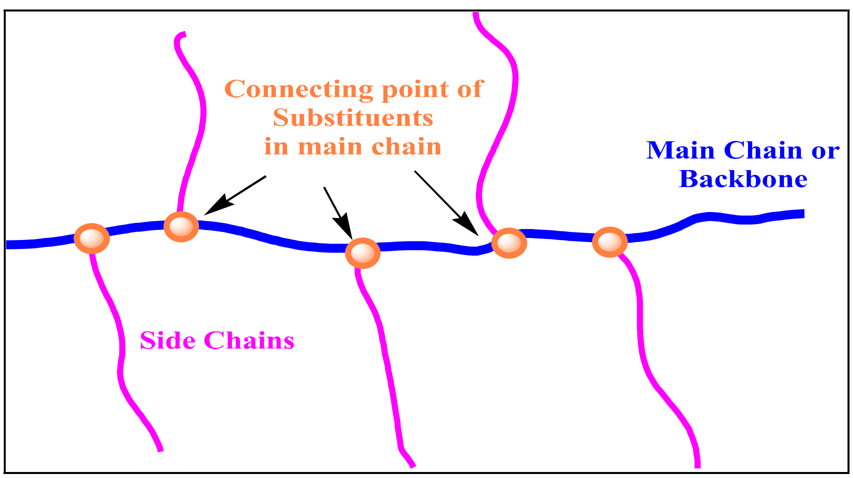


Figure 2.7 Schematic representation of a graft polymer

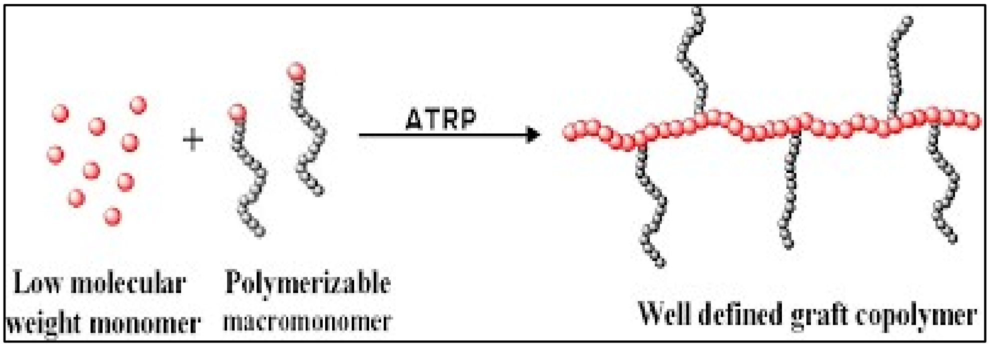


Figure 2.8 Generalized structure of a graft copolymer

2.14 Co-Polymers

When two or more different monomers unite together to polymerize, their result is called a copolymer and its process is called copolymerization. In copolymerization, monomers may be arranged in random manner or one-by-one sequential manner (Figure 2.9). Monomers typically have a double-bond or a triple-bond that undergoes addition reaction with another molecule to form a new single bond between the monomers.

A polymer derived from more than one monomer with acrylamide is known as polyacrylamide copolymer. In this study, a copolymer is derived from synthetization between acrylamide monomer and acrylamido-1-propane sulfonic acid (AMPS) monomer. Polymerization of PAM along with PAMPS, double bonds of both will participate in polymerization reactions.

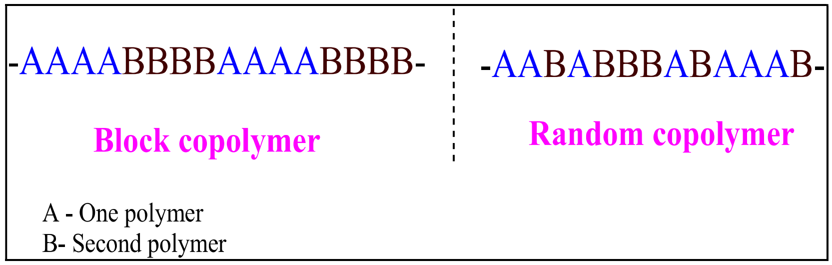


Figure 2.9 Schematic representation of block and random copolymer

2.15 Polyacrylamide (PAM)

Polyacrylamide, poly (2-propenamide) or poly (1-carbamoylethylene), abbreviated as PAM, is a polymer formed from acrylamide sub-units (Figure 2.10). Synthetic water soluble polyacrylamides (PAM), are organic substances that dissolve / disperse / swell in water and thus modify the physical properties of aqueous systems undergoing gelation, thickening or emulsification / stabilization. These polymers perform a variety of functions in aqueous media, including uses as dispersing and suspending agents, viscosity modifiers, stabilizers, thickeners, gellants, flocculants [73, 74].

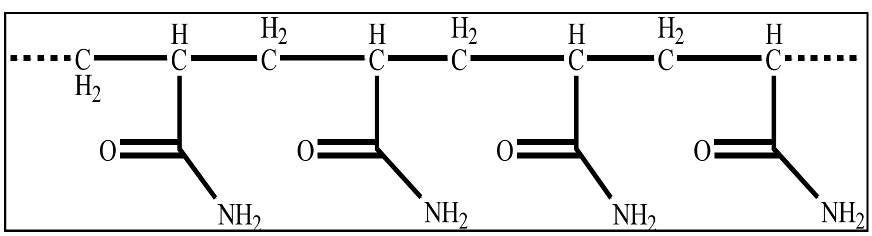


Figure 2.10 Chemical structure of polyacrylamide

2.15.1 Polyacrylamide (PAM) as a dust suppressant

Polyacrylamide is hydrophilic in nature i.e. it displays an affinity for water [75]. Usually, it has repeating units containing hydrophilic groups of the amide ($-CONH_2$) as in Figure 2.11.

The main advantage of the application of PAM as a dust suppressant is its non-toxic nature as well as its biodegradability. Therefore, it finds the extensive usage in industrial applications such as in drinking water and industrial waste water treatment, oil sand tailings treatment, improvements of soil stability, and enhanced oil recovery.

The introduction of PAM as a chemical flocculating agent for wastewater causes suspended particles in wastewater to aggregate. Polyacrylamide is effective in enhancing the stability of soil aggregates and decreases soil infiltration in some areas especially in sandy loam soils. Polyacrylamide is a long-chain synthetic polymer that acts as a strengthening agent, binding soil particles together and holding soils. Parabelo et al. (2019) did an experiment on soil plantation, which indicates that water-holding capacity can be increased without negatively affecting plants [76]**.** Johnson (1984) found that polyacrylamide can absorb water 40 to 500 times their own weights [73]. In another study it was found that water uptake capacity of PAM was found to be 4,520%, which is extremely high [77]. Performance of PAM is determined by the chemistry and formation conditions of the polymer, and also by the chemical composition of the soil solution or irrigation water. PAM can offer significant economic, environmental, and social benefits in the field of dust control.

2.15.2 Environmental Effects of Polyacrylamide

Acrylamide is used to make polyacrylamide, which is mainly used in treating effluent from water treatment plants, improvements of soil stability and many industrial processes. If polyacrylamide enters soil or water, it is broken down quickly by bacteria. The first step of polyacrylamide degradation in nature is its deamination to polyacrylate, which is a more recalcitrant substrate for microbial metabolism [78]. Biodegradation of polyacrylamide begins with amidase catalysed deamination of polyacrylamide to ammonia and polyacrylate. The liberated ammonia is then used as a nitrogen source for growth of the microbes [79]. Although several bacteria and micro-organisms have shown to degrade the carbon backbone, the efficiency and rate of degradation vary to a great extent [80]. Polyacrylamide does not show any toxic effect. Drinking water may sometimes contain polyacrylamide. When polyacrylamide enters human body through any means, its breakdown products leave the body mostly through urine; small amounts may leave through feces and exhaled air.

2.16 Polysaccharides

Polysaccharides are obtained either from tree extrudates or from agricultural crops. Water-soluble polysaccharides have industrial and agricultural applications including viscosity controllers, drag reducers, controlled drug delivery agents, adsorbent polymers and flocculants [81, 82]

Polysaccharides are naturally biodegradable and their shelf life is short. They require high dosage for flocculation. Because of biodegradability, the flocs lose stability and strength in a short period of time. However, by grafting, hydrolysis, and cationization, above properties of polysaccharides can be improved.

Graft copolymerization of acrylamide monomers onto polysaccharide substrates is widely used for property modification of polysaccharides. Biodegradable drag-reducing agents and flocculants based on polyacrylamide-grafted polysaccharides have been widely explored [83].

Among the natural polymers, starch, amylopectin, guar gum, and their products are used as flocculants and retention aids. When polysaccharides are grafted with PAM, they provide the best flocculation efficacy among all the modified polysaccharides. The present research work reports the grafting of amylopectin and guar gum with acrylamide through free radical polymerization technique [84].

2.16.1 Amylopectin

Starch consists of two types of polymers - (i) amylose, the low molecular weight linear fraction, and (ii) amylopectin (AP), the high molecular branched fraction. Amylopectin is usually the major component in the starch granule with α(1–4)-linked glucose linear chains and α(1–6)-linked branch points (Figure 2.11) [85]. The AP has been grafted with acrylamide using a ceric ion induced redox initiation technique.

Due to presence of longer branch chains, its binding capacity increases which enhances its application area. Amylopectin is used in industry for multiple purposes like dye removal, viscosifying agent and treatment of industrial effluent.

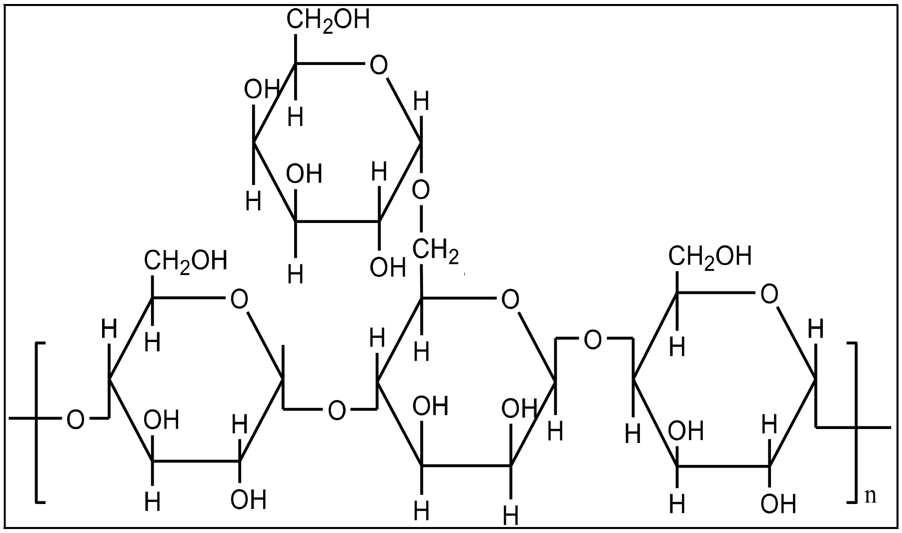


Figure 2.11 Chemical structure of Amylopectin

2.16.2 Guar gum

Guar gum is a carbohydrate polymer derived from the endosperm of two annual leguminous plants Cyanaposisteragonalobus and Cyanaposispsoraloides. Chemically, it is galactomannan consisting straight chain of mannose units attached by β-D-(1→4) linkages, having α-D-galactopyranosyl unit bonded to poly (mannose) chain through (1→6) glycosidic links (Figure 2.12). The greater number of .branches in guar gum is believed to be responsible for both its easier hydration and formation of hydrogen bonding activity [86].

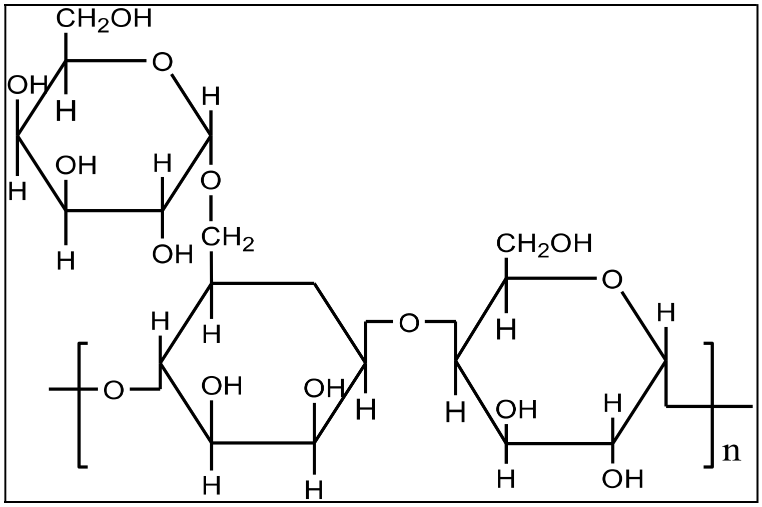


Figure 2.12 Chemical structure of Guar gum

Typically, hydrophilic grafted guar gums are used in the preparation of flocculants, soil treatment and drag reducing agents to treat domestic and industrial water effluent. It has not only traditional role of a viscosity builder for water systems, but also as a hydrogen bonding reagent type chemical for use in such industries such as mining and paper making. Apart from this it is also used as a binder in tablet making and as a colloidal agent in water emulsions [87]. Guar gum is environment-friendly, biodegradable, improving soil water retention ability and also easy to apply. The modified GG with well selected wetting and water retention agents, can boost its water retention and conglomeration effects on the coal powder. Researcher Zhang et al. (2018) conducted an experiment with guar gum as a dust suppressant for unpaved road. The test results indicate that the guar gum developed hybrid dust suppressant has decent water retention, and degradability characteristics [4].

2.17 Poly (2-acrylamido-2-methyl-1-propanesulfonic) acid (PAMPS)

2-Acrylamido-2-methylpropane sulfonic acid (AMPS) is a reactive, hydrophilic, sulfonic acid acrylic monomer used to alter the chemical properties of wide variety of anionic polymers. PAMPS is water-soluble, forms gels when cross linked, and acts as a strong anionic polyelectrolyte (Figure 2.13).

PAMPS are used in industrial coating and adhesive agent. Sulfonic acid group of PAMPS gives the ionic character over a wide range of pH. Anionic charges from PAMPS fixed on polymer particles enhance the chemical and shear stabilities of polymer emulsion. Water molecules bind strongly to ionic and polar sites on the polymer chain of PAMPS and its co-polymers [88].

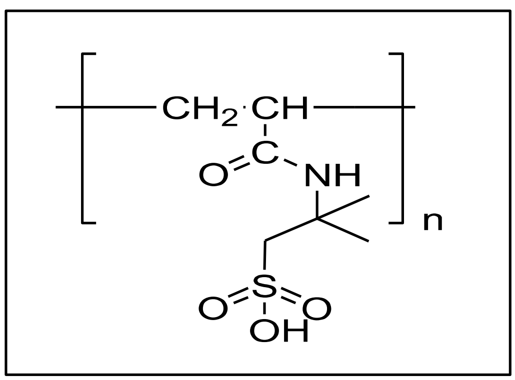


Figure 2.13 Chemical structure of PAMPS