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An overview on Impacts on human health and environment of bitumen fumes evolved from construction industries

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ABSTRACT

Good quality road infrastructure plays a vital role in the growth of economy and is back bone of GDP of a country. Demands of good quality roadways are increasing day by day, creating an over consumption of natural recourses and degradation of environment. The construction of highways, their management and maintenance requires a lot of raw materials and energy. However, pavement industries should keep in mind the more and more protection of environment and sustainability. Asphalt mix plant emits bitumen fumes and other inorganic and organic emissions. This article is focused on the study of theses emissions and their adverse effect on human health and environment. It is seen that temperature ranges from 170ºC to180ºC leads to an increase of PAHs, heterocyclic aromatic compound emissions, large extent of fumes and aerosols causing chronic health and environmental effect. These emissions can be controlled by reducing the production and placement temperature of an asphalt mix from 20 to 60ºC by using additives to reduce binder viscosity and enhance asphalt mixture workability and also by using WMA technologies.

KEYWORDS: Bitumen fumes, WMA, PAHs, gaseous emission, asphalt mix

Introduction

Bitumen was used as a binder and an adhesive have been used for over 5000 thousand years because of its viscoelastic properties[1]. The bitumen was used around 3800 BC. The Egyptians have used bitumen in their mummification as cement and waterproofing purposes. However use of bitumen as such is very difficult as it is very susceptible to temperature. It was used in construction applications because of their durability, water-resistant, strong adhesiveness and most acids, alkalis and salt resistant characteristics and its ability to form strong cohesive mixtures with mineral aggregates known as concrete mixture. They deliver the elastic, viscoelastic and viscous behaviours as their temperature and/or loading rate changes.

According to the report published by Allied Market Research (12 feb 2020), the India bitumen industry was pegged at $196.7 billion in 2018 and is estimated to reach $257.0 billion by 2026, growing at a CAGR of 2.8% from 2019 to 2026. The report provides an extensive analysis of the market dynamics including drivers & restraints, major winning strategies, market size & projections, competitive landscape, and major segments[2]. Figure 1 shows amount of bitumen used in different parts of world. However human health and environmental issues associated with bitumen, fluctuating international crude oil price and increase in use of alternative of bitumen such as concrete in roadway construction applications are expected to restrain the growth of market.

The term bitumen is more generic, which according to the ASTM, relates to "Mixtures of hydrocarbons of natural or pyrogenous origin; or combinations of both, frequently accompanied by their non-metallic derivatives, which may be gaseous, liquid, semi-solid, or solid, and which are completely soluble in carbon disulfide[1]." In usual commercial practice, the term bitumen is restricted to the semi-solid or solid bitumens which include asphalts, tars and pitches. The latter two are derived from stocks obtained by destructive heat action on crude oil fractions, coals, or other organic raw materials. In 1595, Sir Walter Raleigh discovered a thick viscous lake in the jungles of Trinidad. This was to be the largest natural deposit of bitumen ever found and was used extensively until the mid 1970s for caulking (waterproofing) the seams of ships. Large-scale industrial use of bitumen started with exploitation of natural bitumen deposits in Trinidad, with first commercial shipment arriving in England in 1840's. In the late nineteenth century, attempts were made to utilize rock asphalt from European deposits for road surfacing and from this; there was a slow development of the use of natural products for this purpose followed by the advent of coal tar and a later of bitumen manufactured from crude oil[3].

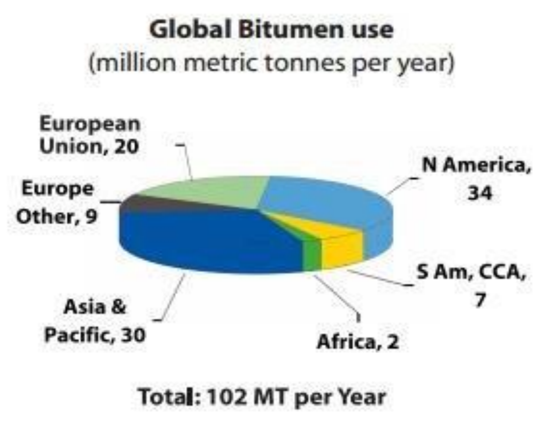

Fig.1. Pattern of bitumen used globally

Bitumen is very complex organic mixture; consist of high molecular weight aliphatic and aromatic hydrocarbons, cyclic alkanes, PAH and heterocyclic compounds along with small percentage of hetero-atoms like nitrogen, sulphur and oxygen and small amount of metals (e.g. Iron, nickel and vanadium)[2]. These three elements are called heteroatom, may have considerable effect on bitumen properties[3].The precise chemical composition and structure of bitumen varies according to source of the crude oil from which bitumen has been taken. The chemical composition of bitumen is shown in Table 1.

Table 1.Chemical composition of bitumen (As Per SHRP, 1993)

Constituents	Amount (in %)
Carbon	70-85
Hydrogen	7-12
Sulphur	1-7
Nitrogen	0-1
Oxygen	0-5

Robert N. H. et al.[4] explained that the bitumen consists of two chemical groups called asphaltenes and maltenes (Fig. 2).

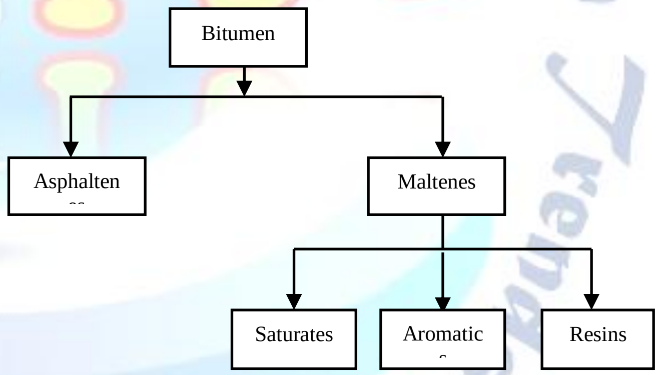

Fig.2. Main chemical types present in bitumen

A typical composition of bitumen is shown in Figure 3. The asphaltenes are highly polar complex aromatic materials having high molecular weight (1000-100000). They have a particle size of 5-35 nm and a hydrogen / carbon atomic ratio of ~1:1. The asphaltenes constitutes 5-25% of the bitumen. Bituminous Materials with high asphaltene content will have higher softening points, higher viscosities and lower penetrations than those with low asphaltene contents. The maltenes can be further subdivided into three small groups: saturates, aromatics and resins. Saturates comprise straight and branched-chain aliphatic hydrocarbons together with alkyl-naphthenes and some alkyl-aromatics. The components include both waxy and non-waxy saturates and form 5% to 20% of the bitumen[4]. Resins are dark brown in color, solid or semi solid and being polar in nature, they exhibit good adhesive properties. Resins acts as dispersing agents or peptisers for the asphaltenes. Resins provide adhesion properties and ductility for the bituminous materials.

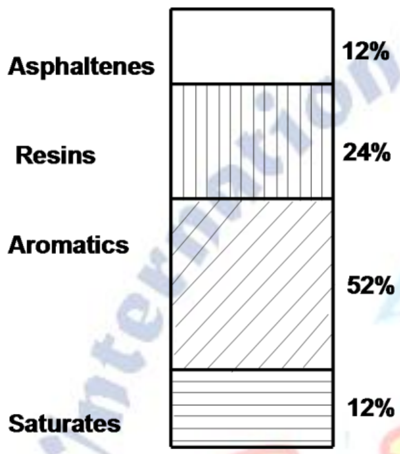

Fig. 3. Percentage composition of different constituents in bitumen

Resins separated from bitumens are found to have molecular weights ranging from 500 to 50,000, a particle size of 1 to 5 nm and H/C atomic ratio of 1.3 to 1.4. Aromatics comprise the lowest molecular weight naphthenic aromatic compounds in the bitumen and represent the major proportion of the dispersion medium for the peptised asphaltenes. They constitute 40 to 65% of the total bitumen and are dark brown viscous liquids. The average molecular weight range is in the region of 300 to 2000. The chemical structure of bitumen is given in Figure 4.

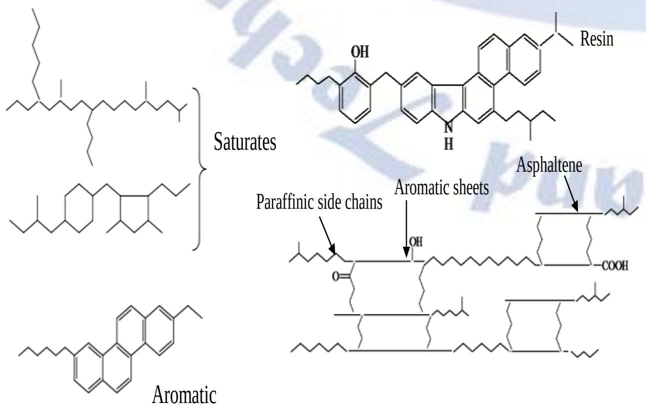

Fig.4. The chemical structure of bitumen[1, 4]

The colloidal model is a traditional model of bitumen behavior, which was first proposed by Nellensteyn[5] in the 1920,s and later elaborated upon by Pfeiffer[5]. The basic premise of this model is that colloidal micelles, consisting of moderately polar molecules surrounding highly polar asphaltenes, are dispersed throughout a continuous, non - polar phase[6]. Bitumens containing highly peptised asphaltenes generally exhibit Newtonian behaviour, while non-Newtonian flow is usually the characteristic of bitumens with lower amounts of dispersed asphaltenes[8]. The physical properties of bitumen depend on chemical nature and percentage quantity of the asphaltenes and maltenes and temperature of the system. Bitumen can be classified as SOL type bitumen (fluid type) and GEL type bitumen (structured type) on the basis of the extent of micelle dissolution[6].Figure 5 shows the schematic representation of these two colloidal types.If the maltenes contain a sufficient amount of aromatics/resins relative to the quantity and quality of the asphaltenes, a SOL structure will be formed, whereas with low aromatic/resin content a GEL structure will result. Temperature affects the degree to which the asphaltenes are dissolved in the oily maltene medium. Most bitumens exhibit these non-Newtonian material properties at room temperature because of their colloidal structure. However, at higher temperatures bitumen also behaves as a Newtonian liquid.

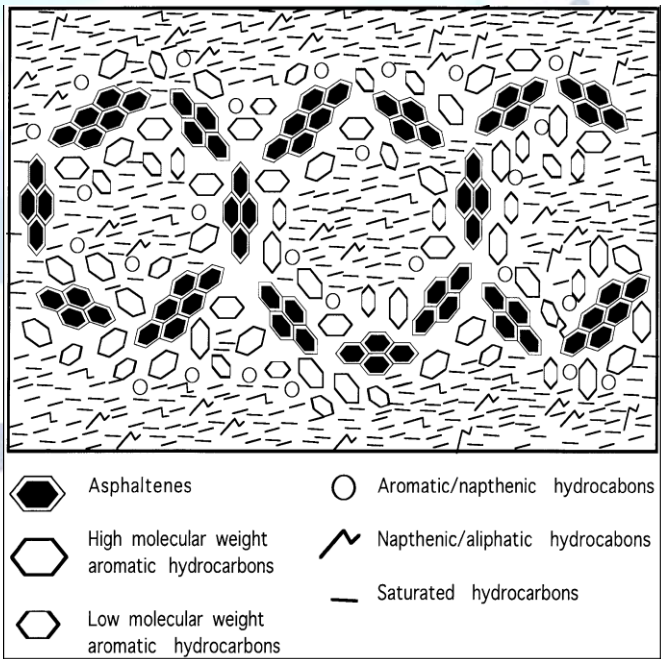

Fig.5. Schematic representation of asphalt structure showing the dispersion of asphaltenes, napthene and polar aromatics, and saturates[7]

Most bitumen is processed hot. During these heating processes vapors are released. When these vapors cool down and condense (aerosols), they are enriched in the more volatile components, also present in bitumen. Because bitumen vapors do not condense all at once workers are at the same time exposed to bitumen vapors and aerosols. In this chapter bitumen vapors and aerosols are sometimes subsumed under the term 'bitumen fumes'. The physical state of bitumen fume cooled down at room temperature varies from light straw- or amber-colour low viscosity liquid to black or dark brown solid or viscous liquid.

The end use pattern of bitumen shows that 85% used in paving, 11% in roofing while 4% of total produced bitumen is used in miscellaneous applications i.e. most commonly bitumen is used as a binder in flexible pavements[40].

The durable Roadway infrastructure is the necessity for a country to increase its and bitumen is main component to bind the aggregate for paving applications. At normal temperature bitumen is stable and does not emit any harmful gases. However, on site most of paving applications are carried out between 170ºC and 180ºC, at which bitumen releases large extent of fumes and aerosols causing chronic health and environmental effect. As discussed earlier the constitution and chemical structure of bitumen depends on the types of bitumen and also the source from where the particular bitumen has been derived. This is why fumes and vapours of bitumen depend upon working conditions like temperature, manufacturing process, modifiers and other additives[8]. Bitumen emissions are very complex and contain high concentrations of various inorganic particulates and organic compounds like aliphatic hydrocarbons, polycyclic aromatic hydrocarbons (PAH) and heterocyclic compounds containing sulphur, nitrogen and oxygen[8].

Types of bituminous binder

The mixture of aggregate, filler and bitumen is commonly known as asphalt, is the main material used in pavement. To enhance the physical and mechanical properties of asphalt some other ingredients like adhesion agents, modifiers and fibres are added to it. In pavement material fillers are also mixed into it to fill out the small voids and filler also stabilize the binder[9]. In 90% case conventional or unmodified bitumen is used in bituminous binders. However, keeping in view the concept of for sustainability and environmentally friendly pavement materials, additives such as recycled rubber or crumb rubber and other plastic wastes are increasingly being used in polymer modified bitumen binders.

Types of asphalt

The asphalts are categorized according to production process and required mixing temperatures- Hot Mix asphalt (HMA), Cold Mix Asphalt (CMA), and Warm Mix Asphalt (WMA).

Hot Mix asphalt consists of a mixture of approximately 95% well graded aggregate uniformly mixed with filler and sometimes additives and bitumen makeup 5% of the mixture[10].To dry the aggregates and to obtain desired fluidity of paving mixture for proper mixing and workability, both the aggregate mixture and bitumen must be heated prior to mixing, this is why is called as Hot Mix. These paving mixtures are produced between the 120ºC to 190ºC temperature ranges. The production temperature of HMA depends on the used bitumen[11]. HMA technology for paving application is most commonly used technology, but it requires high mixing temperature which produces green house gas emission and bitumen fumes.

Cold Mix asphalt is less used in comparison to HMA and WMA and it is used for repairs small patches, potholes, footpaths, storage area and site works. In this technique heating of aggregate on site is not required and prepared bags of paving mixture can be poured directly on potholes or cracks. Only bitumen emulsion is heated at 70ºC or less. In Cold Mix Asphalt bitumen emulsion is used as binder and it is without heating of aggregate at working site. In bitumen emulsion the bitumen is dispersed throughout the continuous water phase which is held by electrostatic charges with the help of suitable emulsifier[12]. Cold Mix asphalt is more convenient to use than Hot Mix asphalt, it can be used when the temperature is not right for HMA installation. Potholes and cracks on the road increases the risks of accident and also damage the vehicle axle and tire, therefore to provide temporary fixing of cracks CMA is better option.

Warm Mix Asphalt

There was confrontation between European countries on requirement of reduction green house gases in Kyoto Treaty (1997)[13]. AS discussed earlier HMA technology requires high working temperature, bitumen fumes and harmful emission, to overcome these disadvantages WMA technologies were developed in favour of the objective set by the Kyoto Protocol to reduce the emission of green house gases at production site of Asphalt mixes. This can be achieved by either lowering the viscosity of bitumen binder or to improve the workability of the mix, thus the production temperature of WMA can be lowered ranging from 20 to 60ºC[14]. WMA technologies include foaming agents, organic additives and chemical packages. For foaming effect water is added to lower the temperature of asphalt mix causing an increase in the volume of asphalt, which results foaming in asphalt mix. To reduce the viscosity of asphalt mix some organic additives (usually fatty amides and waxes) are also added to it which reduces the permanent deformation[15]. WMA technology works at lower production, placement and working temperature, offering several benefits over the conventional HMA. Out of which most important benefit of WMA is the possibility of reduction emission of green house gases without reducing the overall quality and durability of the pavements[16, 17, 18, 19, 20]. Figure 6 shows the reduction in emission using WMA EU Nations. Moreover, the reduction of production temperature also lowers the energy consumption as compared to HMA technology. WMA provides a reduction of nearly 24% in air pollution and 18% in consumption of fuel as compared to HMA[21].

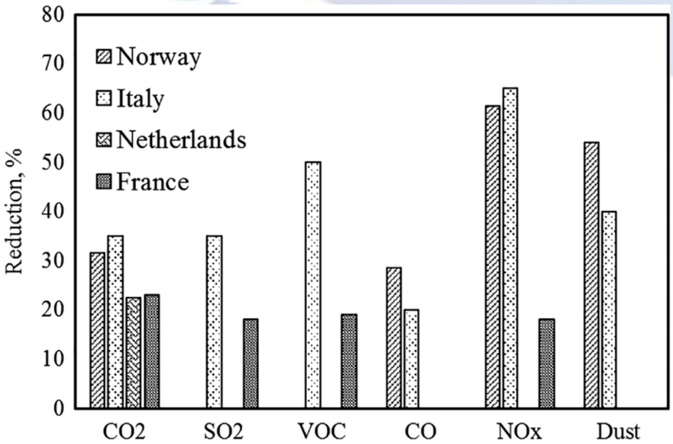

Fig.6. Reduction in plant emissions with the use of WMA for selected EU nations[22, 23, 24]

Types of bitumen fumes and emission

A lot of researches have been done to study the possible environmental impacts of asphalt mix production[12, 25, 26, 27, 28, 41].

The types of bitumen fumes and emissions are depends on the many factors such types of bitumen, source of bitumen, additives and temperature. Table2 shows possible pollutants emitted by asphalt production plant and their source[12].

Table 2 Possible pollutant emitted by asphalt production plant

Pollutants	Source
Dust particles	Aggregate heating and drying process, mineral fillers, storage piles, transportation
Gaseous organic and inorganic emissions	Heating of bitumen, fuel combustion
Noise	Particular parts of production, plant traffic
Odour	Binder bitumen, fuel tank
Waste	Laboratory waste
Sewerage water	Fuel tank
Visual aspects	The design, layout and location of plant

From the above summarized pollutants, few pollutants are described as follows:

Particulates- dust particles

Dust particles are mainly emitted from drying and heating process of aggregate and the amount of dust particles is related to the operating conditions. Transport system like conveyor belt and elevator, material storage and filler silos are some other sources of particulate emission. The dust also contains additives such as fibres, fine recycled materials, hydrocarbons emitted by fuel combustion, slag, ashes and small amount of heavy metals. Particular attention should be paid to the all possibilities of dust production at the asphalt mixing process because serious health and environmental issues are associated with dust emission. Exposure to these particulate matter in the environment have the capacity to cause numerous health problems, people who live near the asphalt mix plant with high particulate matter (PM) concentration experiences difficulty with breathing, chest pain, cough, sneezing and very small size PM enters into blood stream leading to heart diseases and also lung cancer[29, 30].

Bitumen fumes and Gaseous Emissions

"Bitumen fume" is often used in reference to total emissions, but bitumen fume refers only to the aerosolized emissions of total emissions (i.e. solid particulate matter, condensed vapor, and liquid bitumen droplets) Accordingly, the term "bitumen emissions" is more appropriate for referring to total content of bitumen in air[31, 32, 39].

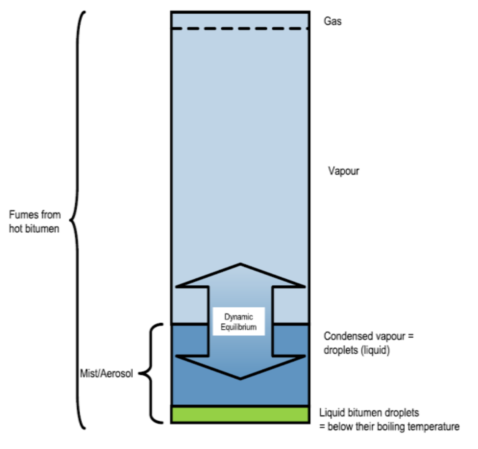

Figure 7. Schematic diagram of bitumen fumes.

Small quantities of hydrocarbon vapours, gases inorganic gases like CO_2, H_2S and NOx are emitted on heating of bitumen. Some heavier molecules in the vapour condense on the nuclei and form aerosol phase. Bitumen fume concentration depends on the type of bitumen used, processing temperature, wind speed and distance from source.

Bitumen fumes and emissions emitted from asphalt mix plants can be divided into two categories: inorganic emission and organic emission.

Inorganic emissions

The SO_2, CO, oxide of nitrogen (NO_x) and carbon dioxide (CO_2) are the common inorganic emissions emitted from asphalt mixing process.

Sulphur dioxide (SO_2)

Sulphur dioxide (SO_2) is liberated in the combustion process in drying drum and depends on the sulphur content in fuel and bitumen. Limestone and other alkaline dust particles absorb SO_2. Slag used as reinforcement in asphalt mix may also increases the SO_2 emissions[33].

The recommended concentrations of SO_2 are 0.20 ppm for a 1-hour exposure period, 0.08 ppm for a 24-hour exposure period and 0.02 ppm for an annual exposure period. Sulphur dioxide affects badly the health of human being and environment also. It forms acid rain, when combines with water and air. Acid rain causes deforestation, acidify the river and other waterways and their aquatic life and corrode building materials and exterior of buildings. Sulphur dioxide affects respiratory systems and causes irritation of eyes.

Carbon monoxide

It is one of the green house gases and emitted during the combustion of fuels in asphalt mixing plant. CO emission is strongly influenced by the aggregate content and the water vapour. Though carbon monoxide does not cause climate change directly, its presence affects the abundance of greenhouse gases such as methane and carbon dioxide.

Oxides of Nitrogen (NO_x)

The nitrogen oxide emissions are produced from the burner when aggregate is heated in the drying drum. Oxides of Nitrogen are produced by the combustion of a fuel-air mixture by oxidation of atmospheric nitrogen with oxygen at high temperatures. The amount of these emissions depends on the nitrogen content of the fuel, the amount of excess air in the drying drum, the pilot flame temperature and the type of the burner.

Carbon dioxide (CO_2)

The carbon dioxide emissions depends directly on the type of the used fuel and the energy consumption by the aggregate in heating process and also on the type of bitumen and the type of heating system of asphalt tanks. The content of CO_2 emissions is evaluated by the production capacity of asphalt mixing plant fuel as it is shown in table 3.

Table 3.Carbon dioxide emissions as a function of production capacity of Asphalt mixing plant and the fuel used[12].

Specific heat consumption per ton of asphalt mixture	Light oil	Natural gas	Butane	Black coal	Brown coal
	Kg CO_2 / ton of asphalt mixture				
70 kWh	18.65	11.63	15.27	23.5	23.61
85kWh	22.65	14.13	18.54	27.99	28.67
100kWh	26.64	16.62	21.81	32.93	3373

All of the described inorganic emissions are depends on the heating and drying processes in the drum. Generally, it should be stated that reduction of these emissions are controlled by the combustion processes optimization.

Organic emissions

Organic emissions mainly consist of hydrocarbons and their molecular structure is characterized by the numbers of carbon and hydrogen atoms. In addition, these emissions can also contain oxygen, nitrogen, sulphur and phosphorus. Hydrocarbon emissions are related to organic components and organic fuel used in the production process. These hydrocarbons are formed in the form of steam or reaction products. The most important source of hydrocarbon emissions is the incomplete combustion of fuel. The type of fuel, plan operating conditions and asphalt vapours in the mixing process lead to the different composition of the waste gases with respect to their organic components. Hydrocarbons are mainly emitted from the drying drum. These emissions can be reduced by periodic maintenance of burner and by increasing and optimizing the combustion of fuel. Heating of bitumen at high temperature is another source of organic emissions. In places where the bitumen is heated to working temperature, vapours are generated. Depending on the environmental impact of hydrocarbons and their impact on human health, hydrocarbons are divided into different categories. Polycyclic aromatic hydrocarbons (PAH) are most important because of their toxicity. Some of these polycyclic aromatic hydrocarbons (PAH) can be carcinogenic to human body under prolonged high-level exposures. The amount of these dangerous hydrocarbons in the bitumen is very small. Only a small amount of these emissions occurs at production temperatures which rarely exceed 200 °C.

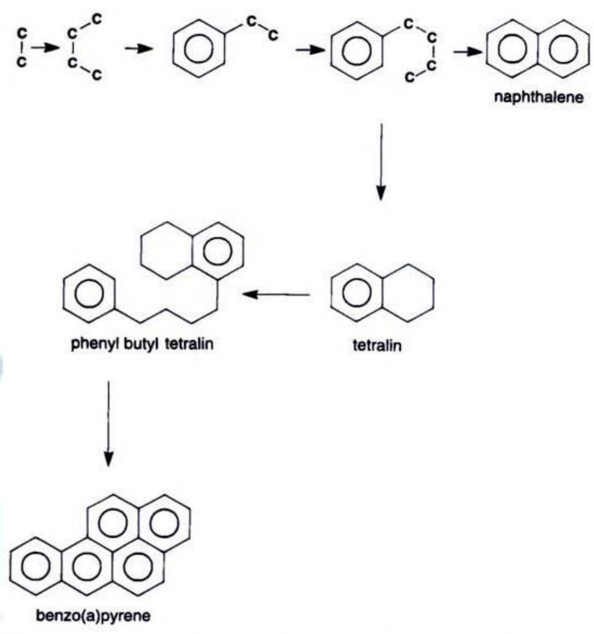

Figure 8.Possible mechanism for the formation of PAHs during combustions[34].

The maximum temperatures involved in the production of bitumen from crude oil, ranging from 350-500 °C not high enough to initiate significant PAH formation, which requires pyrolysis or combustion and typically takes place at temperatures above 500 °C. The principal refinery process used for the manufacturing of bitumens, vacuum distillation, is effective at removing polycyclic aromatic hydrocarbons, including PAHs with 3-6 unsubstituted, fused rings. At elevated temperatures, the small amount of 3-6 ring PAHs remaining in the residue are found in the aerosol fraction of the fumes.

The properties of a PAH depend on its size (number of rings) and the topology of the system[35] (type of ring linkage) 35. Another chemical property of a PAH is the reactivity of its highest occupied molecular orbital. This property makes it a Lewis base and allows it to stabilize according to the Lewis Octet Theory. More specifically a PAH behaves as an electron rich pi-system. PAH compounds are also known to have acutely toxic effects and/or have mutagenic, teratogenic, or carcinogenic properties[37]. Some PAHs are metabolized to carcinogenic species. The classic example is benzo(a)pyrene- 7,8-diol-9,10-epoxide (BPDE), (Figure 9). So several of the PAH are procarcinogens[38].

Odour

Bitumen is the main source of odour. Odour is emitted during the filling of the bitumen tank and also when the mixing unit is emptied into the containers or trucks. The smell depends on the type of bitumen. The usage of recycled material can produce a smell during heating, especially if the recycled material has high moisture content. During plant operation, all the practical steps should be taken to ensure that the odour would not escape out of the plant area. There are several ways how to reduce odour, e.g. usage of products and fuels which produce less odour, reduction of the production temperature of the HMA mixtures or by usage of (chemical) additives which reduce the odour.

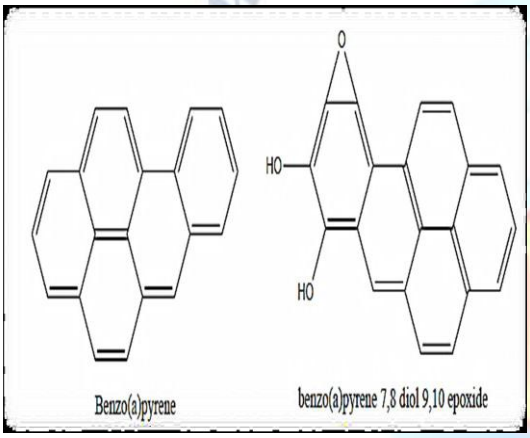

Figure 9. Benzo(a)pyrene gets metabolically converted to mutagenic BPDE through several metabolic steps[36]

Conclusions

Emissions can be reduced by choosing appropriate asphalt mixing plant, its operation and identification of environmental impact. Knowledge about emissions and their concentration in the plant is important for preventive measures. A regular monitoring should be practiced on measurement of emissions concentration and the pollution risk. The plan which clearly defines the complex long-term strategy for reducing the environmental impact should be established for asphalt mixing plant. The choice of specific measurement techniques and solutions which are appropriate to the particular situation will therefore depend on the location and many other factors. Right knowledge of the production process along with the input variables control can leads to a reduction of negative environmental impact along with other cost savings e.g. fuel consumption costs. The timely maintenance of the asphalt mix plant, the control and handling with hazardous materials and recycling are also very significant in the process of saving the environment.

The sustainable development of road transportation which depends on the road infrastructure is the main goal of the technical policy in almost all of the countries. One of the solutions of the sustainable development problem of road transportation is also the saving of materials and energy related to construction or reconstruction of the roads and highways. In this context, we can argue that the development of road construction will be related to the use of environmental technologies. By the reusage of road building materials, the recycling of materials, the using of industrial secondary products, the using of new binders and the using of less energy consumption technologies reduction of gaseous emissions and greenhouse gas emissions will be achieved.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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