# PAH and Benzene emissions reduction at ACT

## A systematic approach to the investigation of emissions at asphalt plants in the Netherlands

*Master thesis shortened version*

Chiara Vishnudatt

Internal supervisors
Dr._ir. S.R. Miller
Dr._ir. J.M. Oliveira dos Santos

External supervisor
ir. R.H.J. Diele

UNIVERSITY OF TWENTE.

TWW TWENTSE WEG- EN WATERBOUW BV

ReintenInfra

*April 2024, Civil Engineering and Management, University of Twente, Enschede*

# Table of Contents

# List of figures and tables

# 1. Introduction

This research aims to cover a trending topic manifested in the asphalt production industry, namely the emissions during production. To ensure the continuation of this industry, it must comply with the legislation set by the Dutch government. This industry must be sustainable, circular, and still meet the client’s requirement of high-quality products.

## 1.1 General background

A good road is indispensable as it continues to contribute to economic prosperity and societal advancement [1]. Infrastructure, especially roads, are the foundation for these advancements and with growing population there is a constant need to expand and manage them. To construct these roads, asphalt mixture is needed, which is made in asphalt plants. The enormous demand for new asphalt and aggregates is leading to their resource exploitation. Therefore, due to this increased demand for asphalt pavement, restricted binder and aggregate supply, the use of recycled asphalt pavement (RAP) has drawn significant attention in pavement engineering from the environmental and economic perspectives [2], propelling this industry toward a more sustainable and circular way of doing business [3].

The usage of used pavement materials is crucial for the circularity within this industry [4]. However, the production of new as well as recycled asphalt is currently not emission free. To limit these emissions the production is regulated by certain laws. Measurements are performed to confirm that the Activities Decree's emission standards are being followed [5]. This decree started to be adopted on January 1, 2016, and regulates the general emission requirements for air for all types of installations in the Netherlands and is set by the government [6]. Before, the Netherlands Emission Directive (NER) Air laid out the criteria for asphalt plant emissions [7]. It obliged the asphalt plants owners to conduct measurements of odour, dust, nitrogen oxide ($NO_x$), sulphur dioxide ($SO_2$), and total hydrocarbons on a yearly basis. With the adoption of the Activities Decree on January 1, 2016, this has changed. From that time on, stricter criteria for polycyclic aromatic hydrocarbons (PAH), and benzene applies. In a relatively short period of time, the standards for benzene emissions were reduced from 5 milligrams/m$^3$ to 2.5 (in the NER) and then to 1 milligram/m$^3$ in the Activities Decree [7].

The above-mentioned regulations require asphalt plants to be tested on different types of emissions. The main ones being formaldehyde, specific hydrocarbons (including benzene), and polycyclic aromatic hydrocarbons (PAH) [8].

*What are PAHs?*

Organic pollutants known as PAHs are widely dispersed in the environment because of both man-made incomplete combustion of fuels like gasoline, diesel, and coal as well as natural occurrences like volcanic eruptions and wildfires. In the atmosphere, PAHs can travel great distances in gaseous and particle forms, affecting soil, vegetation, and people [9]. Due to their numerous sources of combustion and the presence of molecules that pose health hazards, PAH are regarded as representative dangerous substances [10]. PAH are present in bitumen fumes and vapors generated as emissions due to the high temperature processing of bitumen in refineries (up to 288 °C) and bitumen-contained compounds (such as asphalt) [11].

Increased negative impacts on human health have been attributed to exposure to PAH and benzene [12] [13]. Numerous PAHs have been linked to several cancers and are thought to be human carcinogens. Key non- carcinogenic health impacts of PAH exposure in humans include neurodevelopment, respiratory disorders, cardiovascular disorders (CVDs), effects on reproduction, and endocrine conditions. Furthermore, decreased IQ, impaired cognitive development, decreased pulmonary function, hypertension, preterm birth, and delayed foetal growth corroborates the connections of PAH exposure [14].

The US EPA has appointed sixteen of the PAHs out of the more than 30 parent PAHs [9] [15] as priority pollutants for health hazards [9]. To produce asphalt these 16 PAHs are identified as emission from conventional bitumen, the main binder in asphalt [11]. However, in the Dutch asphalt industry there is still a discussion between PAH-8 and PAH-16.

*Benzene*
Another hazardous substance is benzene, which among others is produced out of crude oil. Crude oil is just one of the many substances that naturally contain benzene. The manufacture of asphalt relies heavily on crude oil, which makes benzene a possible threat [16]. Because bitumen is processed during the initial phases of manufacturing, benzene detection is necessary in the manufacturing of asphalt. The manufacturing of asphalt must be monitored with the appropriate technology to protect workers because the processing of this component may result in the emission of benzene gas [16].

Besides the effect these substances have on the planet's health, they are also harmful for humans. The first human case of benzene-induced cancer was documented in the late 1920s [17]. Furthermore, a study conducted in 2020 revealed that after an asphalt plant was built, residents experienced a 25% increase in cancer rates. The study location is a community close to an asphalt mixing factory [18]. Therefore, the emissions in plants must be limited to a certain amount. These substances are released as emission in an asphalt plant predominantly in the drying and heating phase of the production process, especially when RAP is used [19].

## 1.2 Problem statement

For the asphalt industry to become circular, RAP must be used. However, RAP is, among others, one of the materials that have been linked to excessive PAH and benzene emissions [19]. Several asphalt plants who have been unable to comply with the emissions limits set by the legislation, were forced to close their operation [20] [21] [22].

In the past few years, a set of measures have been implemented to reduce emissions and costs on asphalt plants. Some of those include the production of warm-mix asphalt (WMA) [23] and cold-mix asphalt (CMA) [24]. Some of the outcomes of these measures are cost [25] and $CO_2$ emissions reductions [26]. However, most of these measures have been primarily implemented to reduce $CO_2$ emissions, whereas no research has thoroughly been conducted on measures to reduce PAH and benzene at asphalt plants in the Netherlands. Hence, the problem statement is identified as follows:

*There is a lack of measures provided to reduce the emissions of PAH and benzene substances at asphalt plants in the Netherlands, that considers the asphalt mixture components and the production technology.*

Depending on the set up of the asphalt plant, there can be multiple drums where drying and mixing are separated [27]. Therefore, the whole asphalt mixture production process must be scrutinized.

## 1.3 Research objective

Based on the problem statement, the following research objective is formulated:

*To provide recommendations on retrofitting solutions and operation conditions of asphalt plants to reduce PAH and benzene emissions in compliance with the environmental management activity decree (Activiteitenbesluit Milieubeheer) in the Netherlands.*

The overall goal of this research is to contribute to render the production process of asphalt mixtures at the asphalt plants more sustainable with respect to the PAH and benzene emissions.

## 1.4 Research scope

The research scope is set to make this research feasible, therefore the following is applied:

- Only the emissions of PAH and benzene during the production of asphalt mixtures are analysed; Other emissions will not be considered in this research. These substances are analyzed in the production process, therefore at the asphalt plant. The production of asphalt mixture for infrastructure and the associated direct emissions serves as the foundation for this study.
- Furthermore, the research is built on a case study of an asphalt plant, namely the Asphalt plant Twente (ACT).

## 1.5 Main research question and sub-questions

The research objective stated in the previous section can be achieved by answering the following main research question:

*How can asphalt plants in the Netherlands operate sustainably, by reducing the PAH and benzene emissions in compliance with the norms and standards in the environmental management activity decree (Activiteitenbesluit Milieubeheer)?*

This main question is supported by the following sub-questions:

1. Which current Dutch legislation regulates the PAH and benzene emissions at asphalt plants?
   a. Which of the PAH types are subject to regulation?
   b. What are the regulatory maximum values that the emission of these substances can reach?
2. How does the asphalt mixture composition affect PAH and benzene emissions at ACT?
3. How do the asphalt plant set-up and technologies affect the PAH and benzene emissions?
4. How excessive are the current PAH and benzene emissions at ACT?
5. What technical and operational solutions/strategies can be installed/adopted to curb the excess of emissions?

# 2. Research methodology

By achieving the research objective, the implementation of the provided recommendations should enable the asphalt industry to comply with the Dutch legislation on emissions of the substances PAH and benzene. The idea is that the recommendations are to be applicable to any asphalt plant with the same production technology to any given production volume. To provide these recommendations, the research questions as stated in section 1.5 are to be answered. To answer these, several methodologies are to be used, which are presented in this chapter's sub-sections. Each sub-section provides the methodology to answer the sub-questions in section 1.5, leading ultimately to the answer to the main research question, in the last section of this chapter. An overview of the research methodology is given at the end of this chapter.

## 2.1 Research question 1

This first research questions considers the non-technical side of this research, the (Dutch) legislation on the production of asphalt mixtures. This is important as it defines the constraints/conditions for the asphalt plants on emissions produced. The legislation defines which emissions to test on and their maximum values. Literature research will identify the PAH types subject to regulation and the maximum values of the substances PAH and benzene.

## 2.2 Research question 2

This research question considers the composition of asphalt mixtures. A thorough understanding of the composition of asphalt mixtures is needed as background information before analysing the asphalt mixture in relation to emissions. This understanding is provided by literature research. Furthermore, literature research provides a general relation between the different components in asphalt mixtures and the effect of increasing or decreasing such a component, on the emissions produced [28] [29].

The next step entails the case study of ACT, where two sets of data are collected. The first set contains the emission quantities during asphalt mixture production for the PAH and benzene substances. The second set contains the component (aggregates, RAP, bitumen, and filler) input quantity and the time of the input.

It is necessary to specify that the components in the asphalt mixture are expressed in ratios against each other (by weight against the total weight of the mixture), thus conveying the components in percentages. This will be the unit for the components in the asphalt mixture. These percentages are established in the lab and are therefore the theoretical values. The practical values are the ones related to the emissions. These are the ones that will be used during the data processing.

To analyse the relation between the asphalt mixture composition and benzene, it is necessary to integrate the beforementioned data sets (the emission data and the component input quantity). This data integration will be a batch processing one, implemented by python as ETL tool (to extract, transform and load data) [30]. The data set for benzene emissions reveals time against the emissions quantity, whereas the data set for the mixture composition prevails at what time the components are added to the drums. To establish a relation, these two data sets can be integrated on their common parameter, time, creating a time-bound data integration. This way a correlation between the component and the emissions quantity can be analysed. This will be done for each component (aggregates types, RAP, bitumen and fillers). Finally, the output of this integration will establish the relation between the asphalt mixture component against the benzene emissions produced, implementing causal inference [31] [32]. This can be done through a regression analysis. A linear regression analysis can be conducted for each component as independent variable and the emission as dependent variable. The formula for this is:

$$y = \beta_0 + \beta_1 X_1 + \epsilon$$

Where:

- $y$ = the dependent variable, the emission
- $\beta_0$ = the constant or the y-intercept (value of y when all other parameters are set to 0)
- $\beta_1$ = the regression coefficient
- $X_1$ = the independent variable, the different components
- $\epsilon$ = model error (indicates how much variation there is in the estimate of $y$)

The individual relations between components and emissions provide insights into which components are related to the highest emissions, leading to possibly tracing the cause. The linear regression analysis provides insights between the emissions and the individual components. By conducting a multi-linear regression analysis it can be determined which component relates to the highest emissions. However, the linear regression analysis can also be used to indicate this, when comparing the regression coefficient. Additionally, this relation complemented by the beforementioned literature research (secondary data) provides opportunities for strategies to be implemented to reduce benzene emissions.

To analyse the relation between the asphalt mixture composition and PAH, the collected data from ACT is studied. PAH are mainly found in bitumen and bitumen fumes. However, there still lies uncertainty in the contributions of the other mixture components to PAH emissions [28]. Based on the model of Ventura et al. (2015), where PAH stack emissions are modelled for a HMA asphalt plant for Life Cycle Inventory (LCI), this study continuous to relate PAH to the asphalt mixture. The difference lies in the collected data, where Ventura et al. used a standard produced gravel asphalt mix design, this study is based on the collected data throughout the years at ACT where RAP is a component added in the mixture. The mixture components can be extracted in ratios weight against the total produced asphalt weight, where one of these components will be the dependent variable namely the PAH emission. The differences, but also the similarities, in mixtures and measured PAH emissions can establish a relation.

The relation between mixture component and PAH emissions in this analysis establishes which components contribute the most and therefore creating opportunities for strategies to be implemented to reduce this emission.

*Data collection*
Benzene is measured daily at the ACT for each batch of asphalt mixture made, at 15 second intervals. This is done using a benzene measuring device, namely Ion Science Titan [33], which measures benzene emissions solely in the chimney. These measurements are presented in a table with four important columns containing time in the first column, the temperature for the 'black' drum (drum for heating RAP), the temperature for the 'white' drum (drum for heating aggregates) and the last column containing the total benzene emission.

The measurements are automatic measurements, where data gathering is performed without human intervention, providing accuracy [34]. There is no measurement available for benzene per production process (i.e., drying, heating, or mixing). Benzene emission data collected for the year 2022-2023 will be studied, as the Titan was installed in April 2022, therefore only data from this point on is available. Additionally, this is the most recent year and therefore will provide the most up-to-date measurements [34]. Furthermore, a year data provides diverse emissions considering dry and wet season, but also cold and warm seasons. This is important as these seasons affect the moisture content, therefore the heating and drying processes in time, resulting in effects on emission [25] [26]. It is noteworthy that 2022 was not the year for optimal production[1]. Nevertheless, the produced asphalt mixtures during this year do provide an overview of the most produced mixtures in the different seasons and through the optimal production years.

PAH is measured twice a year per asphalt mixture made – on a specific day and time, by TAUW, a specialized contracted firm, on the instructions of ACT. Additionally, in order of the environment service Twente (ODT), annual measurements on PAH are performed by environment service region Arnhem (ODRA). PAH measurements take place for one produced asphalt mixture, three times each for 30 minutes. Therefore, providing three measurements for one asphalt mixture, out of which the corrected average is presented. This value is then measured against the norm. The emissions are measured per $mg/m^3o$ 17 vol %, meaning the results are calculated at normalized conditions (0 [°C], 101.3 [kPa], dry waste gas, with actual oxygen and an oxygen content of 17 [vol.-%]). Due to these periodic measurements, data on PAH emissions require a wider time scope. However, the measurements on PAH started in 2022 with the above-mentioned frequency. Before this it was measured once every four years. Furthermore, due to management transition, available data ranges from 2017 to 2022.

## 2.3 Research question 3

The third research question focuses on the production process of asphalt mixtures. It considers the processes within the production of asphalt mixtures, therefore the plant set up and the technologies used, where PAH and benzene are released. These processes are specific to the plants, as each plant may differ in set up, in terms of technology or machinery used. Therefore, a literature review is necessary, as it will provide an overview of the different types of existing asphalt plants, in relation to emissions [35]. This provides background information for the next step to answer this research question.

[1] The detailed background explanation is given in chapter 6.2

This next step entails the case study of ACT. To get an understanding of how the asphalt mixtures production processes (drying/heating, mixing) affect benzene emissions, a link must be made between different production processes and the emissions. However, in the asphalt plant the emissions are measured at the chimney, therefore, separate emission measurements per process are unavailable. To bridge this gap the data collection of one of the data sets in research question 2 is used, namely the data set where the emissions are provided per time for both the white and black drum. The temperature of these drums provide the time when this drum starts heating. Since these drums are not turned on simultaneously, the emissions can be tracked separately, by extracting them. To analyse the emissions during mixing, a time bound data integration is necessary. This will result in spikes during some minutes in the benzene emissions column, as the batches are mixed within a time span of a minute. Therefore, the data sets from research question 2 will not only provide the relation between emissions and asphalt mixture components, but also the production process, as in this plant the different components are processed in different drums. This relation, complemented by secondary data from the aforementioned literature research,  provides opportunities for operational strategies, plant set-up and technologies to be implemented to reduce emissions. This research question is limited to ACT as case study and to the emission benzene, as the data measurements to establish this relation are only available for benzene at ACT.

## 2.4 Research question 4

The fourth question focusses on the excessiveness of the emissions. To determine this, the emissions from the plant are measured against the norm. The primary data from question 2 and the quantitative output of question 1 provide the necessary data to establish how excessive the emissions are at ACT. The output of this question will help determine the reduction in percentage and will therefore be a guideline for finding the suitable strategies or solutions to recommend.

## 2.5 Research question 5

The fifth research question discusses the most suitable strategies and solutions for curbing excessive PAH and benzene emissions at asphalt plants. Literature research (secondary data) will be used to provide strategies. However, to make the strategies implementable, certain conditions must be met. The strategies can have many input angles. Therefore, to remain in the scope of this research, implementable strategies will be evaluated in terms of asphalt mixture components and technology (machinery) used, thus technology and mixture elements that are applicable to the plant set up of the researched asphalt plant, ACT. The second condition is focussing on state-of-the-art strategies for asphalt mixture components and technology to curb excessive emissions. The last condition for these strategies is that they must be able to reduce the excessive quantity of emissions established in research question 4. To validate the strategies on the last boundary, an analysis will be conducted to determine how changes in components and used technology within the plant set up affect the emission of PAH and benzene substances. This will be done with a regression analysis. Because the target variable (emission) is possibly dependent on multiple variables, a single or multi-linear regression can be used [28]. A multi-linear regression can prove valuable to determine the dependent variables' values under a specific condition for each of the independent variables. Through this analysis the impact of the strategies can be evaluated. The formula for a multiple linear regression is:

$$y = \beta_0 + \beta_1 X_1 + \cdots + \beta_n X_n + \epsilon$$

Where:

- $y$ = the predicted value of the dependent variable (emission)
- $\beta_0$ = the y-intercept (value of y when all other parameters are set to 0)
- $\beta_1 X_1$ = the regression coefficient ($\beta_1$) of the first independent variable ($X_1$ ; the impact of increasing the independent variable's value on the anticipated y value)

- … = the other independent variables (components of the mixture)
- $\beta_n X_n$= the regression coefficient of the last independent variable
- $\epsilon$ = model error (indicates how much variation there is in the estimate of $y$)

Because of the different independent variables in the context of a multi-linear regression analysis, this analysis is done through an ETL tool. Therefore, python is used. Through this analysis, the strategies are within the research scope and reduce the emissions below set values by Dutch legislation.

## 2.6 Main research question

The recommendations to be given at the end of this thesis are based on the case study of the asphalt plant ACT. They must comply with Dutch legislation, which is accounted for in research question 1. The case study provides the relation between the asphalt mixture components, production process (asphalt plant set up and technologies), and the emissions, which are revealed through answering research questions 2 and 3. The output of these relations alongside the literature research (secondary data), will provide opportunities for strategies to reduce the emissions. The number of excessive emissions at the plant (research question 4) against the quantitative answer from research question 1, provide the necessary reduction of emissions for finding strategies or solutions (research question 5). The opportunities for strategies (research question 2 and 3) combined with the strategies from research question 5 provide the recommendations to answer the main research question. An overview of this research is presented in figure 1.

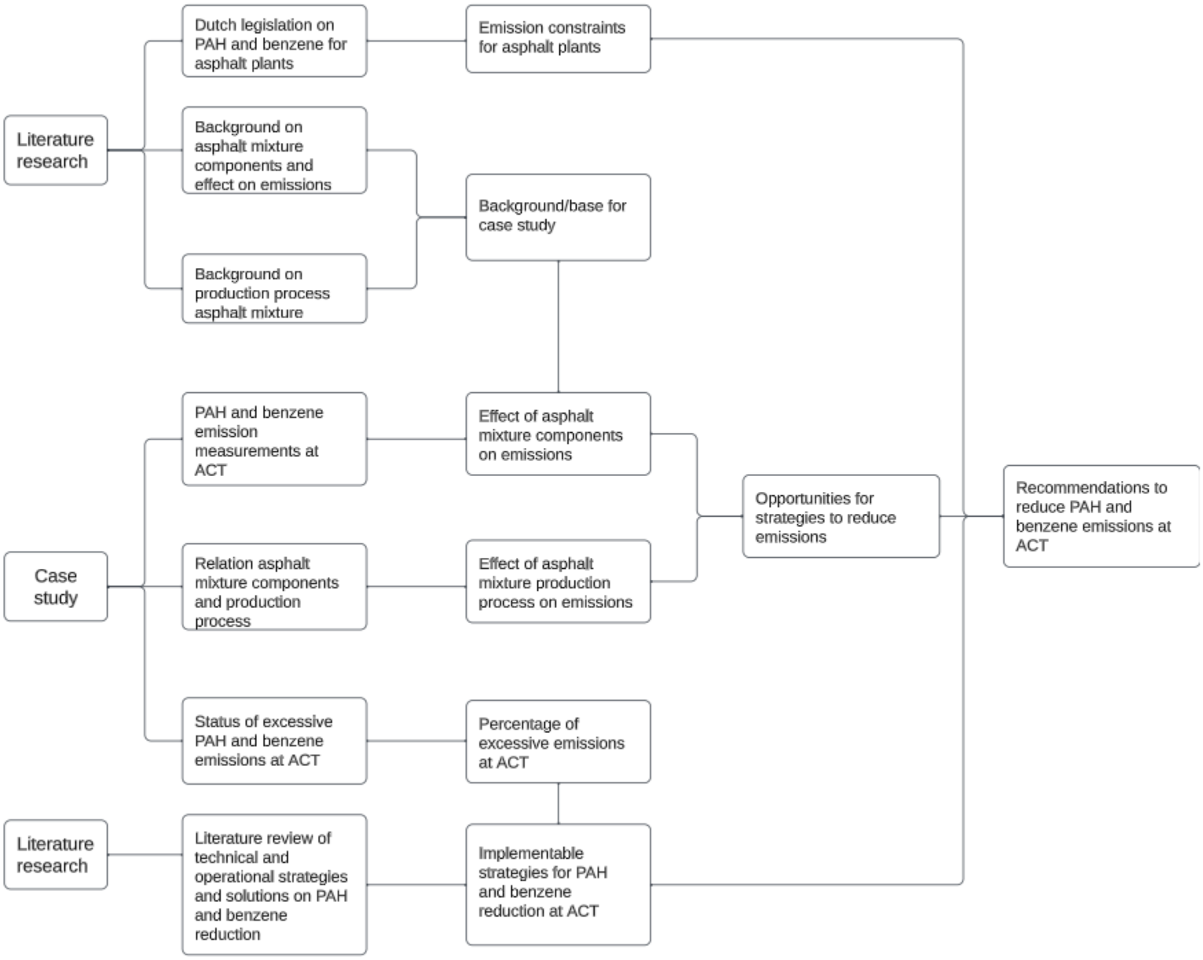


*Figure 1 Overview of the research methodology*

# 3. Expected Contributions

This chapter explains the relevance of this research. The relevance of this research is assured in contributions to science and to the practitioner, therefore the two sub-sections.

## 3.1 Contributions to science

PAH and benzene can contribute to many health hazards as explained in chapter 1. Therefore, the quantities established by law must not be surpassed. Within the asphalt industry, the excessive emissions are topical as they have caused several operational closures [8] [22] [21]. This research addresses this, by providing recommendations to reduce these emissions, to comply with the Dutch law and therefore prevent closure of the plants in the Netherlands. To the best of the author's knowledge and based on a search of peer-reviewed databases, no prior work has empirically investigated the reduction of PAH and benzene emissions at asphalt plants, through establishing relations between asphalt composition, production process and PAH and benzene emissions based on time-bound data integration. Therefore, this research will fill in this gap.

## 3.2 Contributions for practitioners

The implementation of the recommendations will help asphalt plants reduce PAH and benzene emissions in compliance with the law. This helps the practitioner to comply with the evolving legislation in the Netherlands and therefore avoiding imposed fines and closure, resulting in financial profitability. It will also contribute to a healthier environment for personnel at the plants and neighboring residents. By improving the sustainability of the asphalt plants through this research, the reputation of the practitioner may improve. Finally, this research does not only contribute to the Dutch asphalt industry, but also to the national health agenda, as the outcome of this research provides better air quality in surrounding neighborhoods of the plants.

# 4. Risk management

This chapter presents the potential risks and how to mitigate them. For this research three potential risks identified.

1. Expected limitations as this research will be built on two case studies, namely ACT. The recommendations will be based on the typical set-up and production processes of this plant, and therefore the emission quantities too. For this research, this plant will be assumed "standard" plant. Also, the goal is to keep the recommendations specific to the PAH and benzene emissions based on asphalt mixture components and operation specifics.
2. Possible data deficiencies; from PAH-8 to PAH-16. The data will be analyzed using measured data of PAH-8 as this is the PAH measured at the asphalt plant. PAH-16 was only tested from 2023 onwards. The recommendations will be based on strategies applied on reduction of PAH-8. However, literature research provides insights into which of the PAH's from PAH-16 and PAH-8 have the biggest effect on health hazards. Therefore, these results can be accounted for.
3. Unavailability of emission quantities per phase of the production process at each asphalt plant. In this case, the overall production of emission per different asphalt mixture will be studied.
4. The deficiency of continuous measurements of PAH at ACT. In this case the available data will be used to only establish a relation between emissions and asphalt mixture components. Furthermore, literature research will be used to fill in the gaps for establishing relations.
5. Overabundance of strategies. Research on the reduction of emissions, shows there are many measures that can be taken. To mitigate this risk the state-of-art recommendations for emission reduction on asphalt plants will be explored within the literature and not just emission reduction in general.

# 5. Background information

The final chapter provides the (theoretical) background of the current legislation on emissions on an asphalt plant. Furthermore, the production of ACT is presented for the last decade.

## 5.1 Legislation

The Environmental Management Activities Regulation outlines the specific "recognized" requirements for the actions during the asphalt production to comply with the Activities Decree's target articles [36]. A target regulation is a standard in the law that companies must adhere to (the activities decree), whereas the activities regulation state the measurement to achieve these standards.

Predominantly PAH was not part of the emissions to be tested on, but Article 5.46, first paragraph, under a, of the Activities Decree on Environmental Management about the emission requirement for polycyclic aromatic hydrocarbons deems it necessary [37]. Therefore, even if the asphalt plants meet the quality requirements of BRL 9320[2] they will also be tested on PAH.

The US EPA has appointed sixteen of the PAHs out of the more than 30 parent PAHs [9] [15] as priority pollutants for health hazards [9]. These are also known as PAH-16 Table 1 PAH-16 as per US EPA. These 16 PAHs are identified as emission from conventional bitumen [11].

*Table 1 PAH-16 as per US EPA [9] and PAH-8 as per Article 1.1 of the Activities Decree*

| Nr. | PAH as per US EPA | PAH as per Art. 1.1 |
|---|---|---|
| 1 | naphthalene (NAP) | naphthalene (NAP) |
| 2 | acenaphthylene (ACY) | |
| 3 | acenaphthene (ACE) | |
| 4 | fluorene (FLO) | |
| 5 | phenanthrene (PHE) | |
| 6 | anthracene (ANT) | anthracene (ANT) |
| 7 | fluoranthene (FLA) | Fluoranthene (FLA) |
| 8 | pyrene (PYR) | |
| 9 | benz(a)anthracene (BaA) | |
| 10 | chrysene (CHR) | |
| 11 | benzo(b)fluoranthene (BbF) | benzo(b)fluoranthene (BbF) |
| 12 | benzo(k)-fluoranthene (BkF) | benzo(k)fluoranthene (BkF) |
| 13 | benzo(a)pyrene (BaP) | benzo(a)pyrene (BaP) |
| 14 | dibenz(a,h)anthracene (DahA) | |
| 15 | indeno(l,2,3-cd)pyrene (IcdP) | indeno(1,2,3-cd)pyrene (IcdP) |
| 16 | benzo(g,h,i)perylene (BghiP) | benzo(g,h,i)perylene (BghiP) |

According to Article 5.46 of the Activities Decree[3] [5] , and norm of BRL 9320[4] [38], the municipality of Hengelo declares to have tested the asphalt plant Twente on PAH-8. However, per February 2023 this municipality now wants to conclude that, in accordance with Section 2.5 Activities Decree, they must additionally test for, other chemicals and appropriate compounds to PAH-16, based on national new findings [39]. On the contrary, according to the Environmental Management Activities Decree

[2] This assessment guideline relates to the certification of asphalt's bituminous bonded materials' environmental hygiene performance and attributes [42]. Furthermore, this guideline also refers to the CROW publication 210, whereby tar-containing asphalt is to remain outside the recycling circuit [35]

[3] In this article the permitted value of emissions are stated for asphalt plants. For specifics visit: https://wetten.overheid.nl/BWBR0022762/2022-09-21/#Hoofdstuk5_Afdeling5.1_Paragraaf5.1.6_Artikel5.46

[4] kiwa norm for Environmental performance and properties of bituminous bound materials; see https://www.kiwa.com/nl/nl/services/certificering/brl-9320-milieuhygienische-prestaties-en-eigenschappen-van-bitumineus-gebonden-materialen/

Article 1.1, there are 8 PAH listed, as seen in Table 1 PAH-16 as per US EPA. Therefore, declaring PAH-8.

## 5.2 Data collection

To collect the data of emissions for the case study, a year should be selected for benzene. This year must predominantly contain diverse emissions considering dry, wet, cold and warm seasons. This is important as these seasons affect the emissions value [25] [26]. However, there are more factors that contribute to the chosen year, which are:

1. Historical trend: considering the production fluctuations in the past decade [41].
2. Representative data: Choosing a year that best reflects the asphalt plant's regular operations, considering elements such as mixture types.
3. Compliance with regulations: Considering environmental regulations that affect the chosen year. Selecting a year that coincides with important changes in operating permits or environmental rules can offer information about compliance and environmental impact.
4. Long-term goals and aspirations. For trend analysis or future planning it could be advantageous to select a recent year to collect the most recent data that may reflect the current operational conditions.

Taking into account the above mentioned factors, the production data of the past decade has been depicted. Table 2 Annual production ACT 2011-2022 displays the annual production from the years 2011 until 2022 for ACT. **Error! Reference source not found.** corresponds with table 2. The trendline in this figure shows the linear annual production. The years closest to this line are less fluctuating. These are 2012, 2013, 2016, 2018 and 2020. To get the most representative data based on the plant's operation and considering future plans, the most recent years should be taken into account. Therefore, the years 2016, 2018 and 2020 should be chosen for data collection. However, there is only available data sets for the year 2022. This year has the lowest production, but the produced mixtures correspond to those of the optimal years. Because the emissions are not measured (cumulatively) per total production, but per batch mixed, the total production does not affect the model.

*Table 2 Annual production ACT 2011-2022*

| | | Mixtures produced | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Production (Kg) | J | F | M | A | M | J | J | A | S | O | N | D | Total |
| 2011 | [redacted] | 0 | 0 | 0 | 6 | 11 | 7 | 10 | 4 | 14 | 14 | 35 | 34 | 135 |
| 2012 | [redacted] | 0 | 0 | 4 | 4 | 9 | 4 | 10 | 4 | 14 | 20 | 36 | 25 | 130 |
| 2013 | [redacted] | 0 | 0 | 0 | 7 | 6 | 2 | 6 | 7 | 12 | 16 | 35 | 35 | 126 |
| 2014 | [redacted] | 0 | 0 | 3 | 4 | 8 | 7 | 5 | 5 | 10 | 13 | 21 | 34 | 110 |
| 2015 | [redacted] | 0 | 0 | 2 | 3 | 10 | 6 | 2 | 6 | 18 | 19 | 19 | 28 | 113 |
| 2016 | [redacted] | 0 | 0 | 2 | 4 | 6 | 7 | 3 | 3 | 8 | 15 | 19 | 28 | 95 |
| 2017 | [redacted] | 0 | 0 | 1 | 3 | 6 | 1 | 3 | 3 | 11 | 12 | 13 | 12 | 65 |
| 2018 | [redacted] | 0 | 0 | 3 | 2 | 3 | 5 | 3 | 1 | 2 | 6 | 13 | 17 | 55 |
| 2019 | [redacted] | 0 | 0 | 0 | 3 | 7 | 4 | 8 | 5 | 8 | 8 | 9 | 22 | 74 |
| 2020 | [redacted] | 0 | 0 | 2 | 3 | 4 | 8 | 4 | 2 | 6 | 10 | 7 | 15 | 61 |
| 2021 | [redacted] | 0 | 0 | 1 | 5 | 3 | 4 | 13 | 4 | 8 | 3 | 13 | 26 | 80 |
| 2022 | [redacted] | 0 | 0 | 2 | 3 | 2 | 9 | 6 | 0 | 6 | 3 | 10 | 13 | 54 |

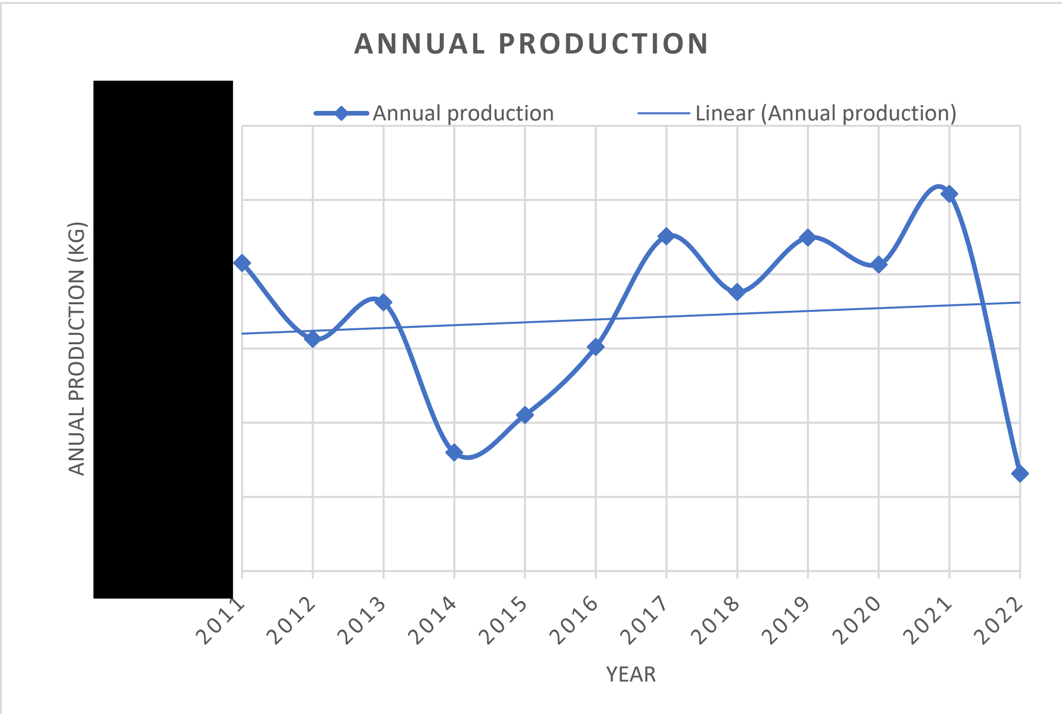


*Figure 2 Annual production ACT 2011-2022 with trendline*

# References

[1] A. Hartmann, "Infrastructure Management lecture sheets. Importance of Infrastructure and Infrastructure management," Enschede, 2015.

[2] X. Zhang, . H. Chen, D. M. Barbieri, B. Lou and I. Hoff, "The classification and reutilisation of recycled asphalt pavement," Elsevier, 2022.

[3] K. Mantalovas, G. Di Mino, A. J. D. B. Carrion, E. Keijzer, B. Kalman, T. Parry and D. Lo Presti, "European National Road Authorities and Circular Economy: An Insight into Their Approaches," *Sustainability,* 2020.

[4] A. Thakur and S. Singh, "Experimental Investigation on Higher Proportion of Recycled Asphalt Pavement Mixture for Road Construction," *International Journal of Innovative Technology and Exploring Engineering (IJITEE),* pp. ISSN: 2278-3075, Volume-8 Issue-8, 2019.

[5] Omgevingsweb, "Activiteitenbesluit milieubeheer," 10 4 2023. [Online]. Available: https://www.omgevingsweb.nl/wetgeving/activiteitenbesluit-milieubeheer/hoofdstuk-5-industriele-emissies/afdeling-5-1-industriele-emissies/%C2%A7-5-1-6-installatie-voor-de-productie-van-asfalt/artikel-5-46/.

[6] Rijkswaterstaat, "Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat," 2023. [Online]. Available: https://www.infomil.nl/onderwerpen/lucht-water/lucht/digitale-ner/afdeling-2-3-lucht/.

[7] R. Arnhem, "Omgevingsdienst Regio Arnhem," 8 December 2021. [Online]. Available: https://www.odregioarnhem.nl/nieuws/asfaltcentrales-in-het-nieuws/.

[8] Arnhem, "Emissiemetingen bij Asfaltcentrale Twente te Hengelo," Omgevingdienst Regio Arnhem, Hengelo, 2022.

[9] Y. Zhang and S. Tao, "Global atmospheric emission inventory of polycyclic aromatic hydrocarbons (PAHs) for 2004," Beijing , 2008.

[10] A. Kamal , A. Cincinelli, T. Martellini and R. N. Malik, "A review of PAH exposure from the combustion of biomass fuel and their less surveyed effect on the blood parameters," Berlin, 2014.

[11] Y. Rasoulzadeh, S. Mortazavi, A. Yousefi and A. Khavanin, "Decreasing polycyclic aromatic hydrocarbons emission from bitumen using alternative bitumen production process," Tabriz, 2010.

[12] R. Akhbarizadeh, S. Dobaradaran, M. A. Torkmahalleh, R. Saeedi, R. Aibaghi and F. F. Ghasemi, "Suspended fine particulate matter (PM2.5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: Their possible relationships and health implications," Iran, 2020.

[13] W. Wiriya, T. Prapamontol and S. Chantara, "PM10-bound polycyclic aromatic hydrocarbons in Chiang Mai (Thailand): Seasonal variations, source identification, health risk assessment and their relationship to air-mass movement," Thailand, 2013.

[14] K. J. Lee and K. Choi, "Non-carcinogenic Health Outcomes Associated with Polycyclic Aromatic Hydrocarbons (PAHs) Exposure in Humans: An Umbrella Review," Korea, 2023.

[15] I. Marigómez, "Oil, Crude," in *Encyclopedia of Toxicology; Biomedical Sciences*, Elsevier, 2014, pp. 663-669.

[16] IGD, "International Gas Detector," 4 April 2023. [Online]. Available: https://www.internationalgasdetectors.com/benzene-detection-in-asphalt-production/.

[17] J. Huff, "Benzene-induced Cancers: Abridged History and Occupational Health Impact," *Taylor & Francis Online,* pp. 213-221, 2013.

[18] M. Song, L. Kwonho , O. Sea-Ho and M.-S. Bae, "Impact of Polycyclic Aromatic Hydrocarbons (PAHs) from an Asphalt Mix Plant in a Suburban Residential Area," Korea, 2020.

[19] VBW, "VBW onderzoeksprogramma reductie benzeenemissie bij asfaltproductie," *Bouwend Nederland,* 2021.

[20] RTV, "RTV Oost," 20 juli 2022. [Online]. Available: https://www.rtvoost.nl/nieuws/2123758/asfaltcentrale-in-deventer-stoot-te-veel-schadelijke-stoffen-uit.

[21] GLD, "GLD," 12 november 2021. [Online]. Available: https://www.gld.nl/nieuws/7445155/asfaltfabriek-nijmegen-dicht-tot-bewijs-dat-gezondheid-niet-in-gevaar-is.

[22] DTV, "DTV," 25 november 2021 . [Online]. Available: https://dtvnieuws.nl/nieuws/artikel/bossche-asfaltcentrale-krijgt-geen-verder-uitstel-om-aan-normen-te-voldoen.

[23] B. Jennings and R. Wirtjes, "Hot-Mix Asphalt vs. Warm-Mix Asphalt," Illinois, 2019.

[24] H. A. Nageim, A. Dulaimi, S. Al-Busaltan, M. A. Kadhim, A. Al-Khuzaie, L. Seton, J. Croft and J. Drake, "The development of an eco-friendly cold mix asphalt using wastewater sludge ash," 2023.

[25] C. G. Arbeider, "Kostenreductie bij de Asfalt Centrale Hengelo," Enschede, 2014.

[26] R. Olthof, "CO2-reductie bij de Asfalt Productie Westerbroek," 2014.

[27] C. Oliveira and C. X. Silva, "DECARBONISATION OPTIONS FOR THE DUTCH ASPHALT INDUSTRY," TNO, 2022.

[28] A. Ventura, T. Lorino and . L. Le Guen, "Modeling of Polycyclic Aromatic Hydrocarbons stack emissions from a hot mix asphalt plant for gate-to-gate Life Cycle Inventory," 2015.

[29] R. Chowdhury, D. Apul and T. Fry, "A life cycle based environmental impacts assessment of construction materials used in road construction," 2009.

[30] ACM, "Association for computing machinery," [Online]. Available: https://dl.acm.org/doi/abs/10.1145/1516360.1516362. [Accessed 16 June 2023].

[31] H. Parikh, C. Vajao, L. Xu and E. T. Tchetgen, "Validating Causal Inference Methods," 2022.

[32] J. Pearl, "Causal inference in statistics: An overview," University of California, Los Angeles, CA, USA, 2009.

[33] EuroIndex, "Euro Index," Euro Index, 2023. [Online]. Available: https://www.euro-index.nl/nl/product/ion-science-titan/. [Accessed 30 06 2023].

[34] VSkills, "VSkills Types of data and Measurement scales," [Online]. Available: https://www.vskills.in/certification/tutorial/data-types-collection-and-accuracy/. [Accessed 15 June 2023].

[35] C. van Gurp, M. Js, W. Nijssen and R. Wesseling, Asfalt in de weg- en waterbouw, 2021.

[36] Rijkswaterstaat, "Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat," 2023. [Online]. Available: https://www.infomil.nl/onderwerpen/integrale/activiteitenbesluit/activiteitenbesluit/eerste-kennismaking/structuur-indeling/.

[37] Staatscourant, "Regeling van de Minister van Infrastructuur en Waterstaat," 2022.

[38] Overheid, "Activiteitenregeling milieubeheer," 10 4 2023. [Online]. Available: https://wetten.overheid.nl/BWBR0022830/2020-07-08/#Hoofdstuk5_Afdeling5.4_Artikel5.37.

[39] HengeloGemeente, "Gemeente Hengelo," 2023. [Online]. Available: https://www.hengelo.nl/Welkom-in-Hengelo/Beheer/Overige-pagina-s/Ontwikkelingen-luchtkwaliteit-en-geuroverlast-rondom-Asfaltcentrale-Twente.html#.

[40] O. NL, "Wetten Overheid NL," [Online]. Available: https://wetten.overheid.nl/BWBR0029789/2021-07-01. [Accessed 20 07 2023].

[41] D. B. Roy, P. Rothery, D. Moss, . E. Pollard and J. A. Thomas, "Butterfly numbers and weather: predicting historical trends in abundance and the future effects of climate change," *British Journal of Animal Ecology*, vol. 70, no. 2, pp. 201-217, 2008.

[42] KIWA, "KIWA," 2023. [Online]. Available: https://www.kiwa.com/nl/nl/services/certificering/brl-9320-milieuhygienische-prestaties-en-eigenschappen-van-bitumineus-gebonden-materialen/.