# The environmental impact of asphalt mixtures production for road infrastructure

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**Abstract**. Developed road infrastructure is a very significant factor which is influencing and conditioning the development of the economy and quality of transportation. Increasing demands for quality of road infrastructure lead to the construction of new roads. Moreover, the importance of keeping pavements in good condition increases proportionately with the increasing traffic. The construction of the road communications, their management and maintenance are material and energy consuming and the problem with the availability and exhaustion of resources is accretive. However, the development of road construction have to respect the protection of the environment, it have to be controlled and sustainable. Sustainable development ensures to meet subsistence for today's and future generations and respects the natural functions of ecosystems. The paper is focused on the analysis of the factors arising from the production of asphalt mixtures for road infrastructure by asphalt mixing plants and their subsequent impact on the environment.

## 1. Introduction

Asphalt mixture is one of the most commonly used materials in pavement constructions and it is a mixture of natural raw materials such as aggregate, filler and bitumen. Some of the additives may be added into the mixture for the reason of influence the performance of the product (e.g. adhesion agents, modifiers and fibers). Bitumen is the black, sticky component (binder) that bonds the aggregate together. Polymer modified bitumen’s are increasingly used to modify the performance of the asphalt mixtures in special applications. Filler is used in asphalt mixture to fill out the smallest voids and to stabilize the binder [1].

The composition of the asphalt mixture has to meet the requirements of the appropriate technical standards. Depending on the asphalt production process and required mixing temperature there are different types of asphalt – Hot Mix Asphalt (HMA), Cold Mix Asphalt (CMA), and Warm Mix Asphalt (WMA).

Hot Mix Asphalt is a mixture of approximately 95% of well graded aggregates, together with filler and sometimes additives. Bitumen makes up the remaining less than 5% of the mixture [2]. These mixtures are generally produced at the temperature roughly between 120 and 190 °C. The production temperature of HMA depends on the used bitumen [3]. The production technology of HMA is the most commonly used technology and the main disadvantages are necessity of using high mixing temperatures and production of greenhouse gas emissions.

Cold Mix Asphalt uses bitumen emulsion as a binder and it is produced without heating the aggregate. Bitumen emulsions are heterogeneous two-phase systems consisting of bitumen and water. The bitumen is dispersed throughout the continuous water phase in the form of discrete globules, which are held in suspension by electrostatic charges stabilized by an emulsifier [1].

Warm Mix Asphalt mixtures are produced at temperature roughly between 100 and 140 °C, and thus they are also known as low temperature asphalts. These mixtures have properties and performance which are equivalent to conventional HMA [3].

The world production of asphalt mixtures is estimated to be about 1.500 million tons per year [1]. The statistics presented by The European Asphalt Pavement Association (EAPA) [4] have shown that approximately 300 million tons of hot and warm mix asphalt were produced in Europe (figure 1) in 2017 and to this day more than 90% of the 5.5 million kilo meters of roads in Europe are made of asphalt mixtures. The Figure 1 is showing the overview of total production of hot and warm mix asphalts in Europe from 2000 to 2017. Nowadays, in the Europe there are approximately 4.500 asphalt mixing plants, more than 10.000 companies are producing and/or paving asphalt, 180.000 people working in the asphalt industry and the industry has an estimated turnover of roughly 30 billion Euro [5].

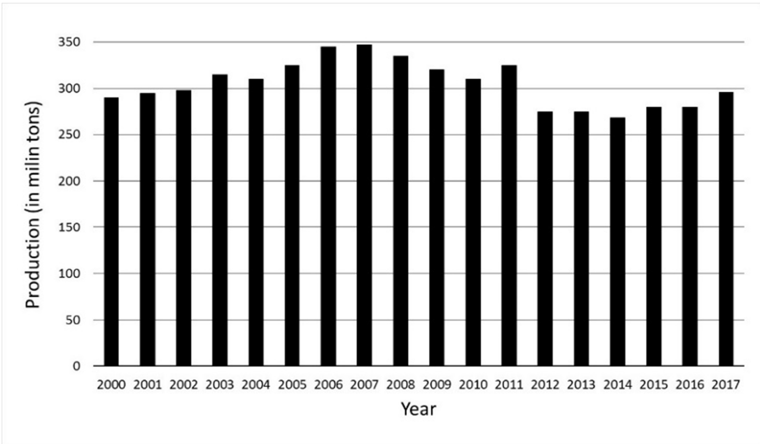
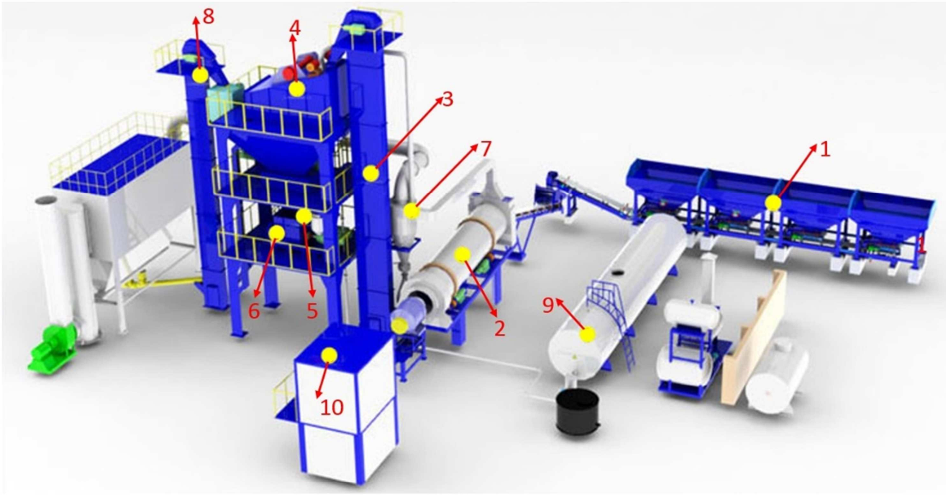



**Figure 1.** Total production of HMA and WMA in Europe from 2000 to 2017 (in million tons) [4].

## 2. Asphalt mixture production process

Production of asphalt mixtures is performed in a fully automated fixed or mobile mixing plant. Typical plant production capacities are 100-300 tons per hour [1]. There are two main types of plants - batch mix plants and drum mix plants. In batch mix plants (predominate in Europe) the mixing process is performed in a mixing unit (Fig. 2 - No.6) (called also as the pug-mill). In the case of drum mix plants is the mixing process carried out in the drum. The complete plant operation of asphalt mixture production is commanded and controlled by the electronic controlling system located in the control unit of the plant (figure 2 – No.10).

The batch mix plant´s production process consists of the following steps. The aggregate is loaded from storage piles and it is placed in to the cold aggregate supply system (figure 2 - No.1). Then, the aggregate is transferred in to the drum dryer (figure 2 - No.2) (typically gas-fired or oil-fired) by conveyer strand. The dust and flue gases are drawn off from the drum dryer by the ventilation unit into the dust catcher (figure 2 - No.7). In the next step, the aggregate is transported from the drum dryer into the vibrating screens (figure 2 - No.4) by the hot aggregate elevator (figure 2 - No.3), where it is separated on particular fractions and dropped into hot aggregate storages according to its size. From these storages is aggregate batched into the weighing system (figure 2 - No.5) and after that goes into a pug mill (mixing unit), where it is mixed and coated with bitumen. Bitumen is pumped from a heated bitumen supply system, weighed, and added into the pug mill. The specified amount of filler is added to the pug mill from filler supply system (figure 2 - No.8) at the same time. After the mixing time (depending on plant type and mixture type) the hot mix is transported into a hot storage silo or it is dropped directly into a truck and hauled to the job site.




1 Cold aggregate supply system 2 Drum dryer 3 Hot aggregate elevator 4 Vibrating screen 5 Weighing system
6 Mixing tower 7 Dust catcher 8 Filer supply system 9 Bitumen supply system 10 Electronic controlling system

**Figure 2.** Batch mix plant scheme [6].

## 3. Analyse of possible environment impacts of asphalt mixtures production by mixing plant

A lot of studies are dealing with the possible environmental impacts of asphalt production [1] [7 - 11]. It should be noted that the consequences of the different types of impacts depend on the many factors and thus can be considerably different in many cases. The possible impacts are listed in the following paragraphs in accordance to importance.

Impact related to the normal operation of mixing plant – it may be a permanent impact (e.g. from the drum dryer) or temporary impact (e.g. due to the loading of storage piles);

Impact resulting from unplanned incidents - these impacts are difficult to quantify because they are unexpected in nature and may be the result of various circumstances;

Impact related to changes in operating conditions – e.g. changes in mixing temperature;

Impacts related to the commissioning and decommissioning of the mixing plant – e.g. impacts resulting from the planned filling, service or maintenance works.

**Table 1.** Possible pollutants emitted by asphalt mixing plant and their source [1].

| Environmental impact (pollutants) | Source |
|---|---|
| Particulates - dust particles | Aggregate drying process, aggregate heating process, filler system, storage piles, material transport. |
| Gaseous organic and inorganic emissions | Heating system, fuel combustion process. |
| Noise | Particular parts of production, plant traffic. |
| Odour | Asphalt binder (bitumen), fuel tank. |
| Waste | Laboratory waste. |
| Sewerage water | Fuel tank. |
| Visual aspects | The design and layout of the plant. |

These above mentioned impacts lead to the production of emissions of many different pollutants. The most common pollutants emitted from asphalt mixing plants are particularly dust particles, gaseous organic and inorganic emissions. The noise, odour, waste, sewerage water and visual aspects are also important from the pollution point of view. Possible pollutants emitted by asphalt mixing plant and their sources are summarized in the table 1 and they are described in more details in following parts of the article.

### *3.1. Particulates - dust particles*

Dust emissions are related mainly to the first phases of the asphalt production. The amount of dust depends on operating conditions. Drying and heating process of aggregate is the most important source of the dust emissions. Other sources of dust emissions are: material storage, material transport system (conveyor belts, elevators) and filler silos. Aggregates include certain percentage of fine fractions. These fine fractions can be emitted during the heating process by mechanical or thermal effects (separated by a hot gas flow in the drum). The produced dust consists of aggregate particles but may also contains particles of additives such as fibers. The dust can also contains binder particles when recycled material is used. The dust can contain also hydrocarbons as a result of the fuel combustion process in relation to the type of fuel. Moreover, the dust can also contains a small amount of heavy metals if waste oils are used. It is necessary to give attention to the dust that comes from some types of artificial aggregates which are used as a substitution for natural aggregates. The slags and ashes are also used as a substitutions. In this case, the special attention is needed. Silica dust may occurs if some types of aggregates are used.

The dust concentration depends on the type and moisture of the used aggregates, the method of treating materials in the drum, the amount and temperature of the waste gas, the rate of the waste gas in the drum, the shape of the extraction chimney and the performance of the plant.

Dust can be emitted from the complex filler system - starting with loading of storage silo from trucks, next with transportation of filler by hoses or screws (pneumatic or mechanical transport) and ending with adding the filler to the mixing unit. The filler system is a closed system with the additional filter accessory and under normal conditions small amount of emissions is emitted. Depending on the climatic conditions (dry weather in combination with wind), dust (especially fine fractions) may be emitted from storage piles of aggregates and also when the material is unloading from the trucks or when storage piles are filling. Dust can be whirled up by the traffic and can be standing in the air. Dust can be emitted from all parts of the system, where dry fine fractions are processed: conveyor system (conveyor belts, etc.), sieves (sorting), weighing, mixing units filling and dry mixing (without bitumen). Particular attention should be paid to the possible dust production during maintenance.

With regards to the information mentioned above, there is a lot of dust emissions sources produced by asphalt mixing plant and their production depends on many different factors, thus the many actions are necessary to be done to minimize the generation of these pollutants. The main prevention concerning dust emission problems should be to try to avoid its production, e.g. to keep the emitting processes in a closed systems with a negative air pressure or additional actions should be performed such as covering, moistening, hooding, and ducting. The main solutions for the reduction of emitted dust particles are to use effective dust extractors, ventilation and filtration systems.

### *3.2. Gaseous emissions*

Gaseous emissions emitted from asphalt mixing plants can be divided to inorganic and organic emissions. The most common inorganic emissions are sulphur dioxide ($SO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$) and carbon dioxide ($CO_2$).

*3.2.1. Inorganic emissions.* $SO_2$ (Sulphur dioxide). The main source of sulphur dioxide $SO_2$ is the combustion process in the drying drum. The formation of $SO_2$ is influenced by the sulphur content in the fuel (mainly petroleum or brown coal). $SO_2$ is absorbed by some types of aggregates (limestone) and also by an alkaline dust layer in the dust filter. Other materials, such as slag, may also increase $SO_2$ emissions.

CO (Carbon monoxide). This emissions are mainly related to the combustion process in the drying drum as well. Fuel combustion is affected by direct contact of the pilot flame with the aggregate. The incorrect geometry of the drying drum, where the combustion space is too small, can also lead to deficient combustion of the fuel. In addition, CO emission is strongly influenced by the content of fine aggregate fractions and the water vapour content.

$NO_x$ (Nitrogen oxide). The nitrogen oxide emissions are produced mainly from the burner in the drying drum. They 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 excessed air in the drying drum, the pilot flame temperature and the type of the burner.

$CO_2$ (Carbon dioxide). The production of carbon dioxide emissions depends directly on the type of the used fuel and the energy consumption by the aggregate heating process and also on the type of treated bitumen and the type of heating system of asphalt tanks. The content of $CO_2$ emissions is determined by the production capacity of asphalt mixing plant and depends on the type of the used fuel as it is shown in table 2.

**Table 2.** Carbon dioxide emissions as a function of production capacity of asphalt mixing plant and the fuel used [1].

| 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 | 23.05 | 23.61 |
| 85 kWh | 22.65 | 14.13 | 18.54 | 27.99 | 28.67 |
| 100 kWh | 26.64 | 16.62 | 21.81 | 32.93 | 33.73 |

In the common operational conditions of the plant are the values of $SO_2$ and $NO_x$ emissions significantly lower than the regulation values. It is not possible to give specific requirements for CO and $CO_2$ emissions because of widely relation to the type of fuel used and the construction of burner installation. However all of these emission can be optimized by suitable plant operation.

All of the described inorganic emissions are specially related to the heating and drying processes in the drum. Generally, it should be alleged that reduction of these emissions are associated with the combustion processes optimization.

It is necessary to monitor the combustion process of the burner and also to ensure the maximum effectiveness of the combustion process. The one of the current solutions is to focus on production of Warm Mix Asphalt (WMA) mixtures. WMA mixtures are produced at lower temperatures compared to the commonly produced HMA and it leads to energy consumption and following emission reduction.

*3.2.2. Organic emissions.* Organic emissions consist of a large group of matters generally described as hydrocarbons. Their molecular structure is characterized by a combination of carbon and hydrogen atoms. In addition, these matters 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 deficient fuel combustion. 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 burner maintaining and fuel combustion volume optimizing. Another source of organic emissions is bitumen, which is heated in the production process. 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. Available measured data [12] have shown, that PAH emissions are well below the national limit values, if at all are measured.

*3.3. Noise*

The main sources of noise in the asphalt mixing plant are drying drum, burner (especially air supply), ventilation unit, vertical conveying system and a hopper lift (especially when it is empty). Other associated sources of noise may be traffic noise from loaders as well as the traffic noise from trucks delivering raw materials and delivering the mixture. Operating noise level should not disturb houses located in the immediate vicinity of the asphalt mixing plant, especially out-off normal working hours. The overall solution of noise problems is to shield the emitting source, reduce the noise from the source or both.

*3.4. 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 a high moisture content. During plant operation, all the practical steps should be taken to ensure that the odour won´t 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.

*3.5. Sewerage water*

Possible sources of groundwater pollution are: storage piles of artificial aggregate, leakage or mixing with natural soil, fuel tanks, hot oil for the heating system, pipelines and pumping stations and solvents (laboratory chemicals). In order to prevent groundwater contamination, preventive inspections (especially leakage inspections) should be carried out during operation of the plant. Bitumen tanks can be placed in a concrete base (or similar) to prevent leakage.

*3.6. Waste*

Asphalt mixture production is not a significant source of waste. Almost all of the basic raw materials are delivered in bulk so there is no packaging remained. Waste generated during the production process in the form of failure mixtures is in most of the cases either recycled or used in the construction of roads, e.g. in quarries. The source of the chemical waste may come from a laboratory, e.g. solvents used for bitumen analysis. All of the secondary waste should be recycled or stored according to regulations.

*3.7. Visual aspect*

The dominant features of the asphalt mixing plant are the high filler silos and asphalt mixture storage bins which should be of a neutral colour. Other visual aspects are the steam emitted from the storage tank, storage of aggregates or lighting of the plant area. The visual aspect should be maximized by appropriate landscaping, appropriate layout and fencing.

## 4. Discussion

A lot of environment impacts of asphalt mixtures production are described in the previous part of article. Some of these impacts have a minor or negligible effect on the pollution of environment. Despite this fact, it is still necessary to monitor them because of the prevention. For that reason, the measurements of emissions concentration and the pollution risk monitoring should be practiced regularly.

High energy consumption due to the high required temperature in the asphalt mixtures production (up to 190 °C) and the associated subsequent production of inorganic emission and greenhouse gas emissions appears as the biggest environmental impact of asphalt mixture production. High energy consumption and amount of $CO_2$ emissions depends on the type and condition of the production equipment (asphalt mixing plant), the settings of the combustion units and the type of fuel and other factors.

According to the measured data of the construction company [13] it can be stated that during the production of the asphalt mixture the $CO_2$ emissions were in the range of 13 to 30 kg/tone of the mixture (depending on the type of asphalt mixing plant and type of fuel). The least of $CO_2$ was emitted into the atmosphere during the combustion of liquefied gas, more by the combustion of natural gas and significantly more by the combustion of light fuel oil. It is very useful knowledge that will be used to decide on the type asphalt mixing plant. A positive result is if the amount of $CO_2$ is less than 20 kg/tone of the mixture. The similar results are described also in [1] (table 2).

High production temperature is important for reduction of the viscosity of bitumen and also for elimination of water from the aggregate surface [14]. Reduction of the production temperature leads to decreasing energy consumption. Therefore the reduction in the production temperature of the asphalt mixture production is currently under strong development due to environmental protection and high energy prices.

By usage of dry aggregates, it is also possible to reduce energy consumption during production. For that reason it is important to storage the aggregate in a place where the moisture content can be eliminated as much as possible. For example, only 1% higher aggregate´s moisture leads to increment of the energy consumptions about 14% [15].

As it is mentioned above, the one of the current solutions to reduce environmental impact of asphalt mixture production is to focus on production of Warm Mix Asphalt (WMA) mixtures. WMA is produced at a low temperatures compared to the commonly produced HMA and this leads to the reduction of energy consumption and following greenhouse gas emission. Studies [3] [16], also cited by [17] show, that the WMA production leads to the reduction of greenhouse gas emissions in the same rate as energy savings.

Results of the measurements [18] have shown that energy savings of asphalt mixing plant ranged from 20 to 35 % depending on the WMA technology, moisture content of the aggregate and the type and efficiency of the plant. The energy savings may be equivalent to approximately 1.5 to 2.0 litres of fuel per ton of material. The total energy savings are even greater with usage of recycled materials. The reduction in greenhouse gas emission is closely associated with the reduction in energy consumption i.e. 20 to 35 % reductions in $CO_2$, which is translated into approximately 4.1 to 5.5 kg of $CO_2$ per ton of mixture.

The emission parameters on several WMA projects were measured [19] including carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$) and particulates (dust particles). In general, the results from those measurements indicated lower emissions for WMA compared to conventional HMA.

The performance data of WMA mixtures have shown [3], [16], [20] that WMA will perform equally or possibly better than conventional HMA. WMA mixture exhibited similar or better performance including improved compaction, similar stiffness and rutting resistance, improved resistance to fatigue and thermal cracking, similar or less moisture damage and greater durability compared with HMA [19], [20].

Despite the all of these facts, that the production of WMA mixtures are the good way for reducing the environmental impact of the asphalt mixture production, the production of Warm Mix Asphalt (WMA) remained stable on a low level only about 2.4% of the total hot and warm mix asphalt production ranks to this asphalt. European leader in WMA production is France with a market share of 11.4%, followed by Norway (11.1%) and Denmark (8.5%) [4].

## 5. Conclusions

A general description of the types of asphalt mixing plants, operations and identification of environmental impact is the base for choosing the appropriate emission reduction methods. Knowledge about emissions and their concentration in the plant is important for preventive measures. For that reason the measurements of emissions concentration and the pollution risk monitoring should be practiced regularly.

The plan which clearly defines the complex long-term strategy for reducing the environmental impact should be established for each asphalt mixing plant. Different places (city/countryside), mobility (stationary/ mobile plant), etc. means different individual solutions. Solution applied in one plant, do not need to be applied in the other plant as well as not all emission reducing techniques are relevant to all types of asphalt mixing plants. 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.

Knowledge of the production process in combination 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 maintenance of the asphalt mixing plant, the control and handling with hazardous materials and recycling are also very significant in the process of environmental protection.

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 re-usage 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.

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## References

[1] Environmental Guidelines on Best Available Techniques (BAT) for the Production of Asphalt Paving Mixes 2007 *European asphalt pavement association (EAPA)* (Belgium Brussels)
[2] Asphalt pavements in tunnels 2008 *European asphalt pavement association (EAPA)* (Belgium, Brussels)
[3] The use of Warm Mix Asphalt 2014 *European asphalt pavement association (EAPA)* (Belgium Brussels)
[4] Asphalt in figures 2018 *European asphalt pavement association (EAPA)* (Belgium Brussels)
[5] The European asphalt pavement industry's position statement on the use of secondary materials, by-products and waste in asphalt mixtures 2017 *European asphalt pavement association (EAPA)* Belgium Brussels
[6] The Process of Asphalt Mixing Plant https://pistonclasico.com/wall/the-process-of-asphalt-mixing-plant, last accessed 2019/7/17
[7] Management of Potential Environmental Impact At Temporary Asphalt Plants 2011 *Work in progress 2nd Draft for discussion by Sabita Environmental Working Committee*
[8] The Environmental Impact of Asphalt Plants 2014 *NAPA National Pavements Assotiation*
[9] Preventing Pollution at Hot Mix Asphalt Plants A Guide to Environmental Compliance and Pollution Prevention for Asphalt Plants in Missouri 2004 *Missouri Department of Natural Resources Environmental Assistance Office 1-800-361-4827*

[10] Hot mix asphalt plants emission assessment report 2000 *Emissions Monitoring and Analysis Division Office of Air Quality Planning and Standards United States Environmental Protection Agency Research Triangle Park NC*
[11] Ozer H, Al-Qadi I and Harvey J 2016 Strategies for Improving the Sustainability of Asphalt Pavements. Federal Highway Administration *FHWA*
[12] Emissionen luftverunreinigender Stoffe aus Asphaltmischanlagen beim Einsatz von Ausbauasphalt – am Beispiel ausgewählter hessischer Anlagen. Schriftenreihe Umweltplanung, Arbeits- und Umweltschutz der Hessischen Landesanstalt für Umwelt 1995
[13] Budinsky V 2013 Energy intensity and greenhouse gas emissions in the production of asphalt mixtures *XVI Ivan Poliacek seminar with intern. participation (Bratislava)* pp 107-11
[14] Gabor P 2010 Environmental technologies in road construction and their topicality *Civil engineering*
[15] Bueche N, Dumont A G 2012 Energy in warm mix asphalt *5th Eurasphalt & Eurobitume Congress (Istanbul*)
[16] Croteau J M, Tessier B 2008 Warm mix asphalt paving technologies: a road builder's perspective. *Annual Conference of the Transportation Association of Canada (Toronto)*
[17] Tutu K A, Tuffour Y A 2016 Warm-mix asphalt and pavement sustainability: A review. *Open Journal of Civil Engineering* **6** 84
[18] Black and Green: Sustainable Asphalt, Now and Tomorrow. National Asphalt Paving Association (NAPA), Special Report Number 200
[19] Politano L 2012 Warm Mix Asphalt—A Greener Alternative to Hot Mix Asphalt. A Paper Submitted for the Transportation Association of Canada 2012 Technical Excellence Awards (Environmental Achievement Awards)
[20] D'Angelo J 2008 Warm-Mix Asphalt: European Practice. International Technology Scanning Program, Federal Highway Administration. Report No. FHWA-PL-08-007