



Università Politecnica delle Marche

Master-degree in **Environmental Engineering**

**Impact of Warm Mix Asphalt
technology on airborne pollutant and
Greenhouse Gas emissions**

Advisor:

Eng. Gilda Ferrotti

Co-Advisors:

Prof. Eng. Giorgio Passerini

Prof. Eng. Andrea Graziani

Student:

Mattia Ciampechini

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Introduction

Nowadays, according to the development of an approach towards a “Sustainable growth”, it must be focus specifically on the reduction in raw materials consumption and on the reduction in process emissions. A sustainable approach in the asphalt production leads to the attempt to search for different adoptable technologies less impacting from an environmental standpoint, even considering the possibility of increasing the amount of recycled material. Dealing with this issue, the temperature of the mixture production results to have a key-role, thanks to its connection with the concepts of fuel consumption and pollutant emissions. For this reason, the use of *Warm Mix Asphalt (WMA)* technology to replace the conventional HMA may be a good compromise. Indeed, the production process is the same, the only difference is linked to the aggregate drying and heating temperature, which will be reduced by 20-40°C compared to the HMA one, introducing the dosage of some additives to guarantee a good workability even at lower temperatures.

The objective of this work-thesis is to verify the difference of the emissive impact of the Warm Mix Asphalt technology compared to the traditional Hot Mix Asphalt production and use, in terms of airborne pollutants and Greenhouse gas GHG emissions.

In order to achieve this goal, this thesis will go into detail through specific and reliable real case studies and, when possible, find some estimation method to apply in generic situations and boundary conditions.

First of all, the Chapter 1 is important to introduce the materials involved in the production of asphalt mixture and the different plant configurations (Batch mix plants and Drum mix plants) available. Specifically, the Warm Mix Asphalt is presented as a new challenge, dealing with the possible advantages and drawbacks, and focusing on the production process compared to HMA.

In Chapter 2, the research will go to deepen the problem of pollutant emissions related to asphalt concrete operations: starting from the distinction between conveyed and fugitive

emissions, both particulate matter and gaseous emissions are analysed, focusing on each pollutant and introducing also the impact of GHGs.

In general, the term “asphalt concrete operations” refers to all the process steps, from the production at the plant to the laying-down and compaction stage (road paving): so, each of the following chapters will deal with a specific impacting stage, analysing the type and the potential amount of emissions.

The most relevant stages will be discussed:

- *Dryer–drum emissions;*
- *Silo filling emissions & Load-out emissions;*
- *Transportation & Road paving emissions.*

Specifically, the Chapter 3 deals with the dryer-drum operation: at the plant, asphalt mixture involves drying and heating of the aggregate using a dryer, to prepare it for the bitumen coating. This process represents the highest impact in a plant, in terms of pollution and also energy consumption. The different impact of this combustion process between the use of Hot Mix Asphalt and Warm Mix Asphalt technology is analysed, in terms of:

- *Energy involved:* verify the potential lower energy consumption (fuel usage) adopting WMA technologies and, as a consequence, the decrease in natural resources exploitation (fuel);
- *Emissive impact:* Stack emissions possible reduction connected to the lower temperatures involved.

To discuss these issues and find possible estimation methods, first of all an important research study will be introduced, and secondly, for the estimation of stack emissions (airborne and GHG emissions), a calculation method will be reported, through the use of Emissions Factors Database, with the final comparison between HMA and WMA.

While, concerning the Chapter 4, it deals with the consequence of the mixing stage with the impact in terms of silo filling and load-out emissions: indeed, the asphalt concrete produced is transported into temporary storage silos, and then, the asphalt mixture is dropped from the

storage silos into the transportation trucks, producing significant emissions. Some *predictive emission factors equations* will be obtained starting from two different real case studies; even in this case the chapter will be closed with a clear comparison between HMA and WMA emissive impact.

After this chapters, an estimation in terms of transportation impact concerning two hypothetical scenarios will be done. In this Chapter 5, even the road paving stage will be investigated, but just from a literature review standpoint, because of the lack of mathematical and theoretical reliable estimation methods. This section will be strictly focused on the health impact for worker exposure during the laying-down operations, analysing the differences in using WMA and HMA.

All the acquaintances collected in these chapters will be finally applied to an Italian case study in Chapter 6, to do some observations about stack emissions and to have a clear and complete vision about the entire impact of the process operations.

1- Warm Mix Asphalt: the new challenge

1.1 Asphalt concrete production and laying operations

Since this project thesis concerns the analysis of the impact of asphalt concrete operations on emissions, it is appropriate to consider firstly the materials involved in asphalt mixture and, secondly, the production process. So, in terms of emissive operations, it can be distinguished in plant operations (drying and heating emissions, load-out and silo filling emissions) and laying-down phase at the worksite with the spreading and compaction of the asphalt mixture.

1.1.1 Materials

Asphalt concrete is a material commonly used in construction projects, such as road surfaces; it is basically a combination of 2 key ingredients:

- **Aggregates:** size-graded aggregates constitute over the 90-95% by weight of the whole mixture. Specifically, to increase the quality of the final product, it's required a certain percentage of fine aggregates (less than 74 micrometres in physical diameters);
- **Asphalt binder:** it is also called "bitumen" and it's a co-product of the petroleum-refining system. As the name implies, the main task of this material is to hold the aggregates together, in order to guarantee a performing asphalt mixture. Asphalt binder is present in a percentage close to 5-6% by weight of the mixture.

In general, characteristics of aggregates can change over days: for example, the strength of aggregates can decrease by 50% when they are wet compared to dry sample.

In asphalt production the aggregates used can be *natural*, *artificial* or *recycled*. Natural aggregates come from quarrying, excavating from land deposits and from rivers-marine deposits; they can be igneous, sedimentary, metamorphic or sand and gravel.

While, artificial aggregates can be represented by waste material from other manufacturing processes: the use of synthetic aggregate may be used to increase the friction surfaces, for example.

The final group of aggregates, the recycled ones, is becoming a major source because of the increasing awareness of environmental issues.

Specifically, the gradation is an important property, it's the distribution of aggregate particle size expressed as a % of the total aggregate mass and it has a large impact on processes and on resulting products properties.

British Standard BS EN 13043 specifies aggregate properties and nomenclature which includes their geometrical, mechanical and physical characteristics [1].

Concerning the bitumen, it is composed of a molecular structure of hydrocarbons and other atoms which gives bitumen a semi-solid visco-elastic property at room temperature.

Modern bitumen is produced from a variety of crude oils through a process called fractional distillation: the distillation column of an oil plant is fed with crude oil which is then heated to between 300-350°C. the result is that the lighter fractions (diesel, petrol...) vaporize, while the heavier fractions of crude oil remain liquid and form the basis of various grades of refined bitumen.

As shown in **Figure 1**, around the 85% of the global bitumen is used as asphalt binder in paving applications, as reported in a joint publication of Asphalt Institute and Eurobitume [2].

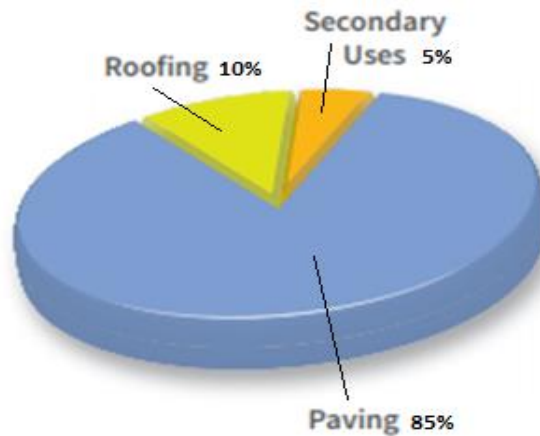


Figure 1. Bitumen Applications (eurobitume_a, 2011) [2].

So, asphalt concrete can be manufactured through the combination of aggregates and refined bitumen, and there are numerous asphalt mixes available, with characteristics that vary significantly between each type, depending mainly on the aggregate gradation and air void volume.

The reason for this variability is connected with the different requirements to meet, which can include heavy traffic or extreme weather conditions and so on.

1.1.2 Asphalt concrete production

The conventional production process of asphalt concrete involves a phase of drying and heating of the aggregates (160°C – 180°C) to reduce their moisture content, preparing these for the bitumen (170°C) coating, obtaining a mixture that is conventionally called *Hot Mix Asphalt-HMA*.

Most asphalt mixes fall into the Hot Mix Asphalt category.

First of all, to better understand the production process phases, it's important to distinguish the different asphalt plants that can operate:

- *Batch mix plants;*
- *Parallel flow drum mix plants and counter flow drum mix plants.*

Batch Mixing Process



Figure 2. Conventional Batch Mix Plant

In this kind of process, the aggregates are transported from storage piles to hoppers, where the material is metered and is transported into a rotary dryer. The dryer has the function of reducing the moisture content of the aggregate and heating, through a combustion process very impacting from the energy and environmental standpoint.

After this unit, the material falls into a bucket elevator and is transferred to a set of vibrating sieves that help to control the size. In accordance with the size, these aggregates were collected in different hot bins, and then an operator will open the bins over a weigh hopper up to achieving the desired mix and weight.

In the newer facilities, at this stage of the process, *Reclaimed Asphalt Pavement – RAP* may be transferred to a separate heated storage bin: RAP is material removed from old pavements, which contains both aggregates and asphalt binder. Of course, it has a lower quality compared to virgin aggregates.

In the meantime, the liquid bitumen is pumped from a heated storage tank to a bucket where it is weighed to guarantee the right quantity for the mixture [3].

The aggregates are dropped into a mixer and dry-mixed for 6 to 10 seconds; after that, also the liquid bitumen is dropped into this mixer, where it is mixed for another period of time.

The total mixing time is less than 1 minute and then, the hot mixture is transferred to hot storage silo (silo filling emissions to control in this case) or dropped directly into a truck (load-out emissions to assess during the step of truck loading) [4].

Drum Mixing Process



Figure 3. Conventional Drum Mix Plant

It is a continuous mixing type process that, differently from the previous batch process, uses the dryer not only to dry aggregate but also to mix dried and heated aggregates with the liquid bitumen.

In fact, after a proportioned size gradation, the aggregates are introduced in the drum at the burner end: in case of “Parallel Flow Drum Mixing Process”, as the drum rotates, the

material moves, as well as the combustion products, toward the other end of the drum in parallel.

More or less at the lower third of the drum, also the bitumen is added and the final result at the end of the drum will be the aggregate well coated with bitumen.

The RAP eventually should be introduced along the drum but as far away from the combustion zone as possible, but with enough length to dry and heat this material before the coating phase.

Concerning the “Counter Flow Drum Mixing Process”, the aggregates move opposite to the exhaust gases flow: it means that after drying and heating, the aggregates won't be exposed to these gases during the coating stage with bitumen. In this way, the stripping of the bitumen by the hot exhaust gases can be avoided.

At the end of the drum the mixture is discharged and conveyed to storage silos, where it is loaded into trucks [3].

Specifically, *Parallel Flow Drum Mixers* have an advantage: there will be a lower load on the downstream PM collection system, because a great portion of aggregate dust is captured at the discharge end of the drum.

However, there is also a drawback of this system, differently from *Counter Flow Drum Mixers*: the mixing of aggregates and bitumen occurs in the hot combustion product (exhaust gases) flow, resulting in an increase of organic emissions, characterised by liquid and gaseous aerosol, connected with the stripping of the bitumen [4].

1.1.3 Laying-down

The laying-down is the final step, it concerns the spreading and compaction of the asphalt mixture at the worksite. This phase is really significant not only in terms of environmental impact but also for the health impact linked to the workers exposure. Unfortunately, it results to be difficult to obtain reliable emissions measurements during the laying-down, depending on the influence of the weather and boundary conditions, dispersion and air dilution, equipment used to gather the data.

1.2 Warm Mix Asphalt & Sustainability

So far, the economy has worked with a “*Production – Consumption – Disposal*” model, according to which each product is destined to reach the end of its life.

Nowadays, the concept of *Circular Economy* represents a system aimed at eliminating waste and the continual use of resources, employing reuse, sharing, repair, recycling and remanufacturing.

It means that this concept answers perfectly the desire of a “*Sustainable Growth*” as a solution to the increasing pressure on mondial and environmental resources exerted by production-consumption relationship [5].

Furthermore, a *sustainable* development embraces reduced consumption of raw materials (fuel), reduced emissions and the possibility of increased recycling while still meeting the development needs.

Anyway, this kind of approach doesn't involve solely the environment, but encompasses 3 interdependent areas [6]:

- Economic growth;
- Social growth;
- Environmental protection.

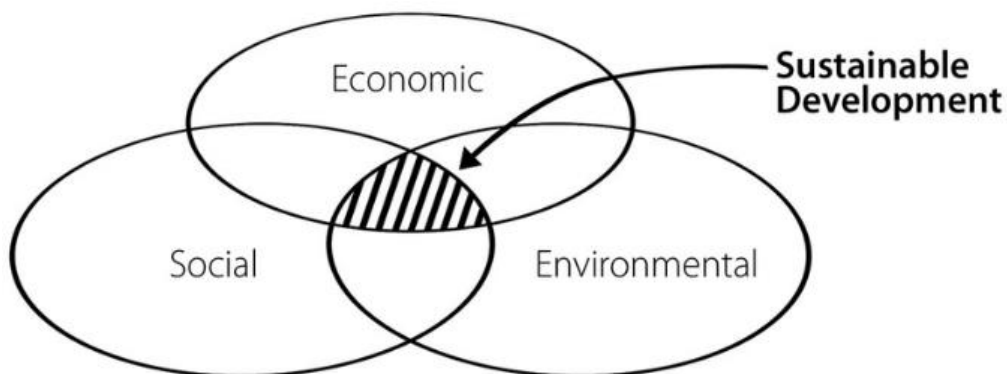


Figure 4. The 3 Pillars of Sustainability

1.2.1 “Sustainable Growth” in asphalt production techniques

So, a circular-kind or “sustainable” project is the starting point for the development of any new product: concerning the asphalt production and use, in order to pursue this target, it’s important focusing on the possible different adoptable technology [7].

Based on the temperature used to manufacture the asphalt mixture in plants, the mixture can be denominated in a different way:

- *Hot Mix Asphalt (HMA)*: mixing temperature between 140°C and 190°C;
- *Warm Mix Asphalt (WMA)*: mixing temperature between 100°C and 140°C;
- *Half-Warm Mix Asphalt (HWMA)*: mixing temperature between 60°C and 100°C;
- *Cold Mix Asphalt (CMA)*: mixing temperature lower than 60°C.

These technologies are very far from being explored at their full potential, because the economic and environmental benefits have not always been properly evaluated.

However, of course, the process temperature has a key-role, thanks to its connection with the concepts of fuel consumption and pollutant emissions: using lower temperatures, the energy consumption for heating and the air emissions could be reduced [8].

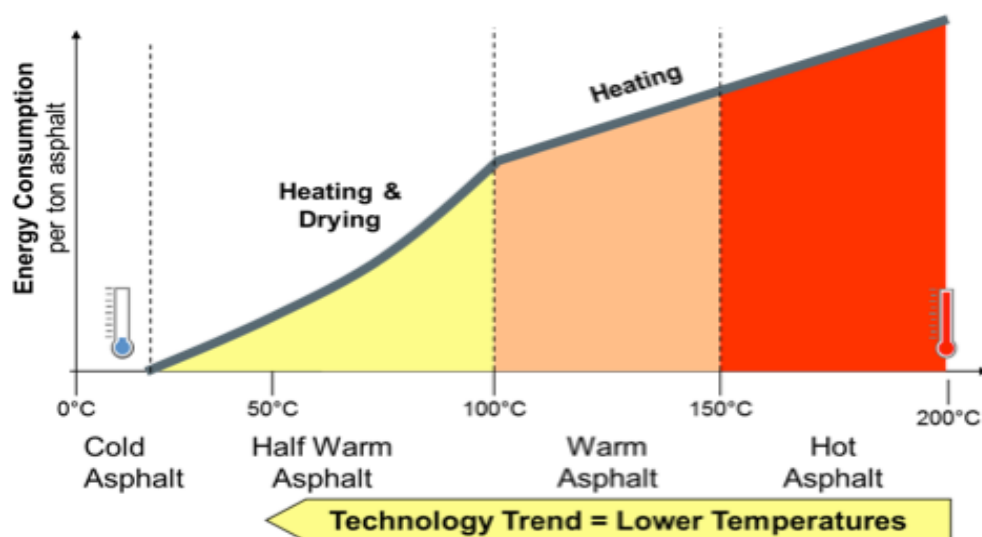


Figure 5. Classification by temperature range [10]

Moreover, it must be emphasized how the use of a different technology, compared to the traditional HMA, can influence also the percentage of recycled asphalt pavement (RAP) involved or the use of other recycled material.

1.2.2 WMA Production Process

Specifically, the *WMA technology* is the major research challenge for the production of environmentally sustainable asphalt pavements, because it allows to reduce both the mixing and compaction temperatures compared to the conventional HMA technology, without significantly altering the mixture mechanical properties, differently from the other technology shown in the previous section [9].

Going into depth, it's possible to stress the main differences in temperature between warm mix asphalt and the hot one:

Process stage	WMA	HMA
Aggregates heating and drying	130°C-140°C	160°C-180°C
Bitumen heating	150°C-170°C	150°C-170°C
Compaction temperature	120°C-130°C	150°C-170°C

Table 1. WMA and HMA typical temperature ranges

In this table, it is shown that in the production process, the temperature difference between the warm technology and the conventional one is just related to the heating and drying of the aggregates; while, concerning the bitumen, it is maintained at the same temperature for both the mixture.

Thereby, being the bituminous mixtures usually composed by 95% of aggregates and 5% of bitumen, it can be considered that the aggregates drying and heating is a relevant step in terms of energy consumption and resulting emissions.

The WMA is usually characterised by a temperature reduction by 30°C-40°C compared to HMA: it could be important defining the possible benefits connected with this reduction.

The European Standards for “Bituminous mixtures” (EN 13108-1 to -7) do not preclude the use of Warm Mix Asphalt. They include maximum temperatures for particular mixtures, but there are no minimum temperatures.

The standards also contain some provisions for dealing with mixtures containing additives, subject to demonstration of equivalent performance.

Indeed, it is known that just at high temperatures it's possible to have a lower viscosity of an asphalt mixture, which means higher workability. So, differently from the conventional hot mix asphalt, for the WMA it must be considered also the addition of a small quantity of additives (organic, chemical...), with the aim of improving the properties of the mixture also at lower temperatures [10].

Specifically, various techniques are used to enable a full coating of the aggregates and subsequent compactability at lower temperature [10].

The most common techniques are presented below [7]:

- *Organic additives*: This kind of additives usually allow a temperature reduction between 20-40°C and can be added either to the mixture or to the bitumen. They are waxes (ex. Paraffin wax) or fatty acids, and must be selected carefully in order to have their melting point above the expected in-service temperatures (to avoid permanent deformations) and to minimize the embrittlement of the asphalt at lower temperatures.

In general, organic additives are added in a range of 1.5-3.5 %, not over 4 % by total weight of binder (including the binder in RAP).

- *Chemical additives*: they do not change directly the bitumen viscosity, but as surfactants they work at the aggregate-binder interface, regulating and reducing the frictional forces. The optimal range of action is at temperatures between 85°C and 140°C. Thanks to these chemical additives is possible to mix bitumen and aggregates and to compact the mixture at lower temperature.

The standard dosage of these chemicals is 0.2-0.5 % based on binder weight.

- *Foaming techniques*: to reduce the viscosity of bitumen, it can be introduced small amounts of water into the hot bitumen. This water will turn into steam, increasing the volume of the binder and reducing temporarily its viscosity: thanks to this expansion, the coating of the aggregates can happen at lower temperature. Moreover, the residual moisture supports the compaction phase on the construction site [10].

Dealing with organic additives, one of the most known is the **Sasobit**, produced by Sasol Wax International [11]: it is a Fischer-Tropsch wax, which is a synthetic aliphatic hydrocarbon wax that at temperature above 115°C is completely soluble in bitumen and for this reason is able to reduce the viscosity significantly.

In this way, Sasobit increases process reliability and reduces also the risk of improper paving operations. The interesting thing is that it starts to crystallize at about 90°C, forming a lattice structure in the bitumen which has a stiffening effect.

When adding the appropriate quantity of this additive, deformation resistance increases significantly, without impairing low-temperature performance.

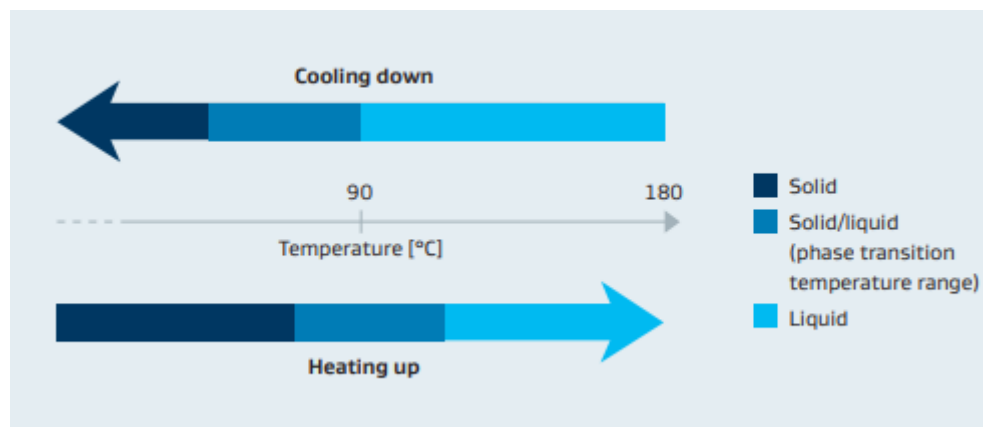


Figure 6. Physical state of Sasobit when mixed into bitumen [11].

So, in general this additive is designed to reduce viscosity, ageing, temperatures (by 18-54°F) and compaction resistance, added in a percentage of about 2 % by bitumen weight [11].

Another commercially available organic wax-based additive is **Asphaltan B**, it is a hard wax obtained by solvent extraction of certain type of lignite or brown coal. The effects are really

similar to Sasobit, but with a solidification temperature around 95-105°C and a dosage range between 2 - 4 % by mass of bitumen [12].

While, concerning the chemical additives, the **Cecabase RT**, for example, is a surface-active agent that can be directly applied into the hot binder, acting as a lubricant during the mixing, laying and compacting process. It allows for easier field compaction and stronger adhesion of the asphalt binder to aggregate with the aim to limit water intrusion, oxidation and protecting against destructive forces such as traffic loading.

In this case, the conventional dosage is 0,25-0,75 % by weight of total mixture: it varies depending on several conditions like production temperature, haul distance, total RAP content [13].

Evotherm is a new generation warm mix asphalt chemical additive, invented by MeadWestvaco in 2003. It promotes adhesion by acting as a liquid antistrip, it may be added at the mix plant or at the asphalt terminal and, once it's mixed into the binder, production temperature can be lowered by 100-130°F than conventional HMA. The optimal Evotherm content is 0,5 % by mass of bitumen [14].

Lastly, regarding the foaming technologies, they can be classified in two different ways: *water-bearing additives* and *water-based processes*.

In case of water-bearing additives, moisture is contained in the solid media (ex. Synthetic zeolites, which are hydrophilic materials) and is released when it comes in contact with hot asphalt binder; then, released water steam generates small bubbles and causes foaming of the bitumen. The expansion of water inside the asphalt results in a reduction of the overall viscosity by increasing the volume and surface area of the binder, due to the latent steam. This mechanism facilitates the aggregate coating and mixture compaction at lower temperature.

While, in water-based foaming process there is no need for using expensive additives, but just mixing a small amount of water (mass ratio of 1-5 % to the asphalt binder) into the hot bitumen, to create microscopic bubbles.

Specifically, as water-bearing additives the two most commonly used are **Aspha-Min** and **Advera**: both technologies consist of a synthetic zeolite that has been hydro-thermally

crystallized. The amount of water held internally by the zeolite is in a range of 18-21 % by its mass, and it's released at temperatures above 100°C.

This water, released as a fine mist, creates micropores in binder that help increase the workability of the mix for even 6-7 h period [12].

In some cases, also combined products can be used to produce WMA, like zeolite with organic additives [10].

1.2.3 WMA advantages & disadvantages

As mentioned before, the problems of this kind of technologies are linked to the fact that, until now, they have not been explored at their full potential: performance, economic and environmental benefits have not always been properly evaluated. For this purpose, nowadays all over the world some research groups are present, to discuss with the target of evaluating and validating WMA technologies, implementing proactive policies, practices and procedures, creating an environment where information about this innovation can be shared.

Environmental impacts

One of the possible advantages of this technology could concern the environment: in literature [40, 41], it is found that, compared to the traditional HMA, the WMA thanks to the lower temperatures used can lead to a relatively important reduction on fuel usage in burners, with a consequent decrease in Greenhouse Gas (**GHG**) emissions and in other airborne pollutants emissions such as particulate matter (**PM**), volatile organic compounds (**VOC**), carbon monoxide (**CO**), Nitrogen Oxides (**NO_x**) and so on [8]. Specifically, Mallick et al. suggests that the temperature reduction seems to be the most effective technique to reduce **CO₂** emissions during asphalt production and pavement construction [39]. This allows the mixture production plants to be located even closer to cities thanks to their potentially lower impact.

Some studies have also measured the possibility of having a slight emissive impact connected to the manufacturing of organic, chemical or synthetic additives used in the warm technology; however, the % of additive used in the mixture is so low, as it has been shown in the previous paragraph, that should not have a relevant effect [9].

The benefits of the use of WMA may be present also during the asphalt paving process with a potential reduction of odours and fumes (dust emissions): it is an advantage not only for the environment, indeed, the working conditions can be improved in terms of health impact and safety for the workers, throughout the lay-down and compaction stage.

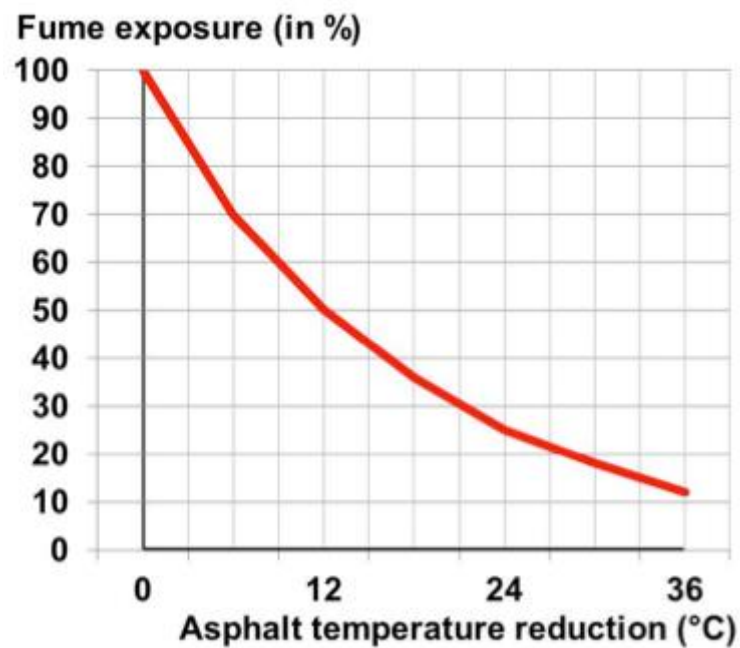


Figure 7. Impact of temperature on working conditions [10].

Following the Literature and looking at the Figure 7 from *EAPA-European Asphalt Pavement Association* [10], the lower mixing temperatures minimise fume and odour emissions: indicatively, as a rule of thumb, the release of fume may decrease by about 50 % for the first 12°C reduction in temperature.

Economic Impact

The use of lower manufacturing temperatures could have some benefits also related to the wear of the asphalt plants, such as the decrease of maintenance costs and also a longer service life of the plant [9].

In the report presented by West et al., an average fuel saving of 22.1% was obtained by a temperature reduction of about 25°C in asphalt mixture [40].

Rondón-Quintana et al. [9] and Mohd et al. [42] showed that, in general, economic benefits can be achieved in terms of energy saving (20 - 35 %), depending also on the average energetic cost in the specific countries. Anyway, there can be a negative aspect of the warm technology related to the costs for the production of the required additives, or related to the possible changes to apply to the asphalt plants manufacturing processes. In most cases, in terms of production costs, J. Croteau et al. explained that the reduction of fuel consumption may help compensate for the cost of WMA additive or equipment [24].

Constructive Impacts

The workability is a fundamental parameter for HMA: it depends on the temperature, which is function of the time in this case. It means that is not possible to transfer this kind of mixtures to a distant place, because if the temperature becomes too low there can be a relatively important loss in the mixture workability.

While, dealing with the WMA, some additives are used to guarantee an appropriate workability at lower temperatures: as presented by Ragni et al, it means not only that it may be possible to use this mixture at higher distances from the plant, but eventually it may be also possible to guarantee winter and night application (extended paving time) [49].

Moreover, Rondón-Quintana et al. [9] showed that in the construction area, it is noted that the viscosity of WMA mixtures is lower than the HMA mixtures one: it may result in a potential earlier opening of the paved road. Nevertheless, concerning the laying-down phase,

Stimilli et al. explained the fact that a lower temperature during this step could lead to a worse adhesion between the layers [47].

Performance: Durability and Resistance

A negative aspect in using the Warm Mix Asphalt is the lack of information about long term performance. In general, the paved roads that have been built up to now using WMA are too recent, making it more difficult to assess any long-term mechanical properties: in fact, there are also several studies, such as by Stimilli et al., showing WMA mixtures properties comparable and even superior compared to HMA ones [47]. While, other researches state that the properties of the WMA are strictly related to the type of additive that can be used and if it is organic or chemical [47, 48, 50].

Indeed, Stimilli et al. showed that thanks to the use of lower temperatures during the production process, from the aging point of view it results in a lower oxidation level: as a potential consequence, the resistance to fatigue and to cracking may be comparable or even higher than in the conventional HMA mixture [47].

This fact has to be considered an important advantage, since an aged asphalt presents a higher stiffness and viscosity, producing a decrease in adhesion between the stone aggregate and the binder, changing the mixture behaviour from ductile into brittle. Specifically, Ragni et al. put the emphasis on the fact that the addition of additive may have a significant effect on the characteristics of the selected bitumen, tending to reduce the effect of age-hardening [49].

However, this lower stiffening of the WMA may result in a decrease of the rutting resistance and so in a higher permanent deformation of the material [9, 47]: in fact, the rutting is the vertical permanent deformation due to the repetitive passing of vehicles and it can be observed in particular in flexible and semi-rigid pavement structures.

Another drawback of the use of the warm technology illustrated by Rondón-Quintana et al. could be the higher sensitivity to water: not necessarily, but there might be the possibility that lower heating temperature can make the drying of aggregate insufficient and, as a

consequence, it can cause problem of adhesion between the stone and the binder, resulting in a bad coating of the aggregate.

Nevertheless, some of the disadvantages connected with the use of the warm technology, may be faced by the use of an optimum grading curve and good quality of the aggregates [9].

Opportunities

Dealing with the introduced concept of *Sustainability*, the WMA technology gives the possibility for manufacturing a mixture using also other materials (polymers or recycled ones, such as rubber from tires, RAP...) for which there is the need to decrease the production and compaction temperatures [9].

Rubber granules, for example, are recycled from old tires and are used to produce the “Asphalt Rubber”: it’s a mixture of bitumen and rubber, which is present in a percentage of about 15% by total weight and it is recognised by the international standard ASTM D-6114-97 (2002).

However, the most important opportunity, suggested even by B.D. Prowell [45] and M.A. Farooq et al. [46], is related to the use of Warm Mix Asphalt is the potential increase in RAP content: in the previous pages has been defined the RAP as Reclaimed Asphalt Pavement, generated from milling operations of existing pavements and composed by aggregates and bitumen. It is necessary to solve the high consumption of raw materials and waste generation from replacing deteriorated pavement [43, 44].

This material-related technology is an opportunity also in terms of environmental impact, allowing to reduce both asphalt binder and virgin aggregate demand: it means that it creates a cycle of reusing materials that optimizes the use of natural resources.

The drawbacks of the RAP are related to the fact that, coming from an old pavement, it’s characterized by inhomogeneity of the mixture, excessive stiffness and bitumen oxidation connected to the aging of this material [48].

The interesting thing is that, as written by Stimilli et al., WMA and RAP can be considered “mutual friends”: these “disadvantages” of RAP can be seen as useful to solve the conventional problems of a Warm mixture, which is generally characterized by low stiffness and low bitumen oxidation, both connected with the lower manufacturing temperatures, and by high water sensitivity [47].

So, these are the reasons that make possible the use of a higher RAP content in WMA mixture, in the range of 25 - 50%, generating resistance to permanent deformation and to moisture damage similar to a traditional HMA mixture [9].

2- Airborne and GHG emissions in asphalt concrete operations

In the previous sections, the discussed topic has been focused on the description of materials, equipment and the process operations employed; on the other hand, this chapter is going to deepen the main problem connected with asphalt concrete: pollutant emissions.

2.1 Airborne pollutant and GHG emissions

In terms of pollutant emissions each individual asphalt plant has its own characteristics which differ according to the type of fuel used, the raw materials used, the hourly potential production and the final product to be made.

Of course, another difference concerning emission values is between plants that have been in operation for years and newly starting plants.

In general, in correspondence of an asphalt plant it's possible to distinguish these kinds of emissions [23]:

- *Conveyed emissions*: These emissions are vented to the atmosphere through some type of stack or vent or pipe. Generally, these are produced during the “drying” and the “mixing” phases and they are characterized by well-defined emission points, with some specific Emission Limit Values – ELV_s to respect;
- *Fugitive emissions*: These emissions, for example, are produced during material loading/unloading operations, laying-down phase, where there is not a specific measuring point; they are emitted directly to the atmosphere.

In general, talking about airborne pollutant emissions (both conveyed and fugitive ones) using chemistry concepts, it's possible to distinguish **Particulate Matter – PM** and **Gaseous Emissions**.

The term “*Particulate Matter*” means the set of liquid or solid substances that, due to their small size, remain suspended in the atmosphere for an indefinite period of time. In the case of a mix plant for the asphalt concrete production, a distinction can be made on the basis of the emission points: PM emitted by the chimney (conveyed) and PM dispersed in the areas characterized by the motion of the aggregates used for the production (fugitive).

For example, fugitive particulate matter emissions can come from aggregate storage piles, generated by loader operations that transport the aggregate to the cold feed unit hoppers, or can be connected with the transfer of these aggregates from the hoppers to the dryer conveyor.

While, dealing with “*Gaseous Emissions*”, there are [23]:

- Inorganic emissions:

- **SO_x – Sulphur Oxides:** this kind of emissions, consisting mainly of sulphur dioxide (SO₂), are largely due to the quantity of sulphur contained in fluid fuels;
- **NO_x – Nitrogen Oxides:** they are usually produced during high temperature combustion processes. However, during the thermal drying and heating process in the asphalt plant, the production of nitrogen oxides is contained since the process temperatures are relatively low (fumes temperature at the chimney 110°C - 140 °C; aggregates temperature 140°C - 180°C). Of course, also the nitrogen content in the fuel and the oxygen content of the combustion process are factors that can influence the production of this compound.
- **CO – Carbon Monoxide:** this emission is mainly associated with incomplete combustion in the dryer drum and it is strongly influenced by the quality of the fuel, the fine-grained content of minerals, the water vapor content and the use of RAP.
- **CO₂ – Carbon Dioxide:** it is related to the consumption and type of fuel used for both the heating process of the aggregates and the heating system of the bitumen tanks. Lower production temperatures reduce both energy consumption and CO₂ emissions; moreover, lower CO₂ values can also be obtained by using natural gas as type of fuel.

- Organic emissions:

- **TOC – Total Organic Carbon:** This organic emission consists of a group of hydrocarbons with a molecular structure characterized by the combination of carbon and hydrogen atoms, but which can also contain *Oxygen, Nitrogen, Sulphur and Phosphorus*. Hydrocarbon emissions are usually due to the use of organic compounds and fuels and in general they take place in the form of steam, as reaction by-product. Another source of TOC emission can be the bitumen vapours produced by the heating phase of the asphalt binder itself.

The TOC represents the sum of Volatile Organic Compounds-**VOC** and methane emissions, and it generally comes from the transport and handling of the hot mix from the mixer to the storage silo and also from load-out operations.

On the other hand, the roadway construction industry plays an important role in economic and development, but it's also a primary source of carbon emission: accordingly, dealing with global climate change, energy conservation and reduction of *Greenhouse Gas (GHG)* emissions have become a critical issue. Specifically, **GHGs** are gases that, by absorbing infrared radiation reemitted from Earth's surface, contribute to the greenhouse effect causing a gradual rise in the temperature of the Earth's atmosphere. Carbon Dioxide (CO₂), Methane (CH₄), Water Vapour (H₂O) and Nitrous Oxide (N₂O) are the most important GHGs, according to the Environmental Protection Agency (EPA).

As it is known, the **Kyoto Protocol** implement the UNFCCC (*United Nations Framework Convention on Climate Change*) objective to reduce the global warming by reducing the GHG concentrations in the atmosphere, to a level that would prevent dangerous anthropogenic interference with the climate system, based on the scientific consensus that global warming is occurring and it is extremely likely that human-made CO₂ emissions have predominantly caused it.

Dealing with this topic, also the **Paris Agreement** has a key-role, aiming at keeping the increase in global average temperature below 2°C over pre-industrial levels, recognizing that this would substantially reduce the risks and impacts of climate change.

It means that the concept of “*Carbon Footprint*” is getting more and more important: it is defined as the total GHG emissions caused by an individual event, organization, or product, expressed as CO₂ equivalent using the 100-year Global Warming Potential (GWP100).

Indeed, the GWP is a measure of how much heat a GHG traps in the atmosphere, relative to CO₂ as key-parameter:

Global Warming Potential - GWP			
GHG	CO ₂	CH ₄	N ₂ O
CO₂ equivalent	1	21	310

Table 2. GWP of Greenhous gas types

Looking at this table, the Methane has a Global Warming Potential 21 times higher than the Carbon Dioxide: for example, 1 ton of CH₄ correspond to 21 tons of CO₂ equivalent. The same reasoning for what concerns N₂O impact.

In asphalt mixture production, this kind of emissions are strictly connected to the combustion process linked to the heating and drying of the aggregate, as a function of the fuel type, the equipment used and the temperature applied [22].

2.2 Emissions Evaluation

Once in the environment, air pollutants can no longer be eliminated. The air protection therefore pursues a single goal: to reduce emissions in the place in which they are generated. From the legislative point of view, the emissions at the source are regulated by the law (i.e. D. Lgs 152/06 in Italy) for each kind of plant depending on the processes and technologies applied. So, in general, to define the impact of a production process the first step is the emissions evaluation: this assessment can be done through direct /indirect measurement or by estimating the emissions.

2.2.1 Direct / Indirect Measurements

To define the impact of an emissive activity or to verify that a plant is respecting the thresholds imposed to each pollutant by the legislation, the best way is the direct/indirect measurement of emissions. The “*direct*” measurement consists of using analyzers which provide a response signal directly proportional to the concentration of the pollutant investigated. While, the “*indirect*” measurement is carried out by analyzers which provide a response signal directly proportional to another parameter to correlate with the pollutant concentration through further measures (i.e. transmittance). To be as reliable as possible, all the sampling methods must respect some operating rules to guarantee the homogeneity of the air flow tested and, depending on the target that has to be achieved, it is possible to make periodic sample or continuous monitoring of the emissive activity, involving of course different equipment (i.e. stack samplers, fixed or mobile control units...).

However, this kind of direct/indirect measurements or continuous monitoring methods may be very expensive and difficult to manage; for this reason, in general, these measurements are applied only in large-sized plants or important industries, while in most cases, it is not possible to guarantee this reliable information.

The alternative is the different approach based on the use of emission factors to try to estimate pollutant emissions starting from the specific characteristics of a process (i.e. equipment, fuel-type, process operations, materials involved, production rate).

2.2.2 Emission factors (EFs)

An important problem dealing with the environmental assessment and the impact of a certain emissive activity, may be that is not always possible to gather direct measurement data or having correct information through the full process.

A partial and approximate solution is the use of *Emission Factors* **EFs**: it is one of the most important emissions quantification tools, used also as a fundamental tool in developing

national and local emissions inventories for air quality management and in developing control strategies.

Indeed, the objective of this kind of indicator is to describe as best as possible an emissive activity, through a quantitative value: so, by definition, the Emission Factor, is a value that relates a certain quantity of pollutant, produced and released into the atmosphere, with the activity associated with the release of that pollutant.

In terms of units of measure, it is expressed as a weight of pollutant divided by a unit of weight/distance/volume/energy/duration of the specific activity. In this way, it is possible to obtain the estimation from different air pollution sources.

These data are commonly available as a function of the type of process, the type of combustion and technology, and they usually come from representative direct measurement on specific case studies and sources of emissions.

For example, it is possible to obtain the emission factors concerning some compounds on the bases of the kind of fuel used for the combustion process.

However, it is important considering that, connected with the EFs, there are also some uncertainties depending firstly on the number of tests performed to determine the factor, but also on the difficulty on carrying out the measurement concerning certain types of emissions.

In general, Emissions factor ratings are characterized as follows [18]:

A- Excellent;

B- Above average;

C- Average;

D- Below average;

E- Poor;

U- Unrated.

While, in terms of reliable sources of *Emission Factors Database (EFDB)* present in literature, there can be different possibilities:

- *EEA-European Environment Agency;*

- *IPCC-Intergovernmental Panel on Climate Change*;
- *US EPA-the United States Environmental Protection Agency*.

Specifically, at European level, the *EEA-European Environment Agency* has adopted the Corinair classification methodology to develop an emissions guidebook, the EEA Guidebook 2019, in order to collect emission factors. *Corinair* is an inventory system that collects emission factors on the basis of a clear definition and classification of the activities, called SNAP 97. In this classification each activity is represented by a code of 3 pairs of numbers: the first couple of numbers indicates the macro sector; the second one, the sector; the third one is about the specific activity linked to the emissions. In the EEA Guidebook 2019 there is a Part B about sectoral guidance chapters, in which the Nomenclature For Reporting “NFRcode = 1.A.2” corresponds to the macro sector SNAP 030313 (concerning Combustion in asphalt concrete manufacturing industry in Corinair classification): 1 = Energy; A = Combustion processes; 2 = Description of sources (**1.A.2.f** – Asphalt manufacture) [19].

Regarding the *Intergovernmental Panel on Climate Change-IPCC*, it is the United Nations body for assessing the science related to climate change: it was created to provide policymakers with regular scientific assessments on climate change, its implications and future risks. The IPCC set out the 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories, composed by 5 Volumes: there is a section dealing with asphalt production, named “Non-energy products from fuels and solvent use”: however, this IPCC database is not so detailed about this issue [20].

While, the *United States Environmental Protection Agency US EPA* has published since 1972 the **AP-42**, a *Compilation of Air Pollutant Emissions Factors* [21]: it contains emission factors and process information for more than 200 air pollution source categories, which are specific industry sectors or similar emitting sources. In this compilation, the emission factors have been developed considering source test data and engineering estimates: information about the estimation of airborne emissions from asphalt production process may be obtained by the **AP-42**, focusing on *Chapter 11- Mineral Products Industry*, section *11.1-Hot Mix Asphalt Plants* [4].

3- Dryer-Drum impact

As it is explained in the previous sections, emissions from Asphalt plants may be divided into ducted (or conveyed) production emissions and fugitive ones.

In the case of the dryer-drum (Figure 8) we are dealing with ducted emissions: it means that they are collected and transported by an industrial ventilation system to be emitted to the atmosphere through some type of stack.

The dryer is used to dry and heat the aggregate up to the mixing temperature, reducing the moisture level of this material, allowing an increase in strength properties and a better coating with bitumen.



Figure 8. Dryer-drum in Asphalt Plant (Sit.2).

In most Drum-mix plants (Figure 9), the bitumen is introduced directly into the dryer chamber to coat the aggregate; while, in Batch-mix plants, the mixing of aggregate and asphalt takes place in separate mixing chambers.

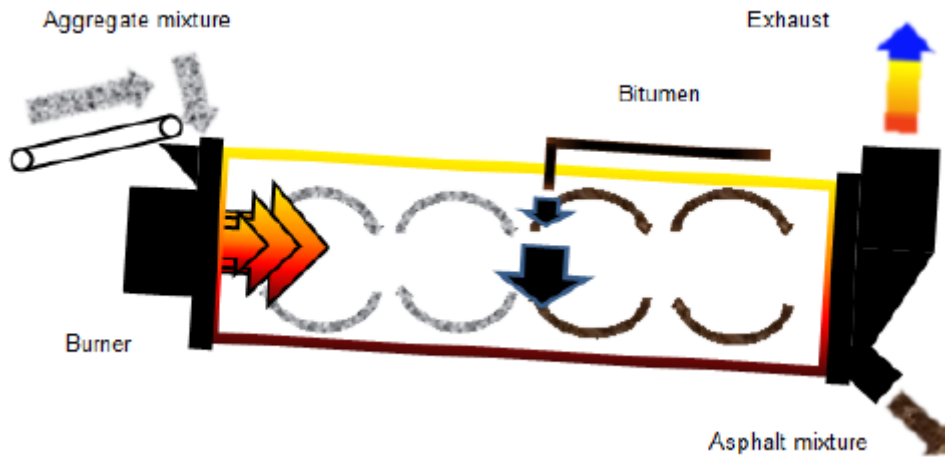


Figure 9. Drum-mix Plant dryer (Sit. 4).

This process step is considered to be the most significant ducted source of pollutants, including products of complete (NO_x , SO_2 , CO_2) and incomplete (CO , VOCs) combustion, PM_{10} from aggregates [3]. Specifically, the organic compounds of various species (including VOC and methane) are usually present in small amounts.

So, in general, the main part of emissions is related to the fuel combustion process and, furthermore, it is estimated that between the 70-90% of the energy used at the asphalt production plant is from this combustion step [4].

It means that unavoidably, concerning the dryer-drum impact, the type of fuel used has a key-role, together with the efficiency and maintenance of the burner and the equipment involved.

3.1 Energy Consumption

The asphalt paving industry is constantly exploring technological improvements that will enhance the material's performance, increase construction efficiency, conserve resources and advance environmental stewardship.

As said before, also current and impending regulations on Greenhouse gas emissions, fumes/odours and energy conservation are making attractive the reductions in asphalt mix

production temperatures. Indeed, WMA, being produced at temperature in the range of 20 to 40°C lower than conventional HMA, may represent the best compromise to achieve as immediate benefit the reduction in energy consumption.

From literature review, the energy gains due to the reduction in fuel usage in the drying of material are in the magnitude of 20-30% compared to the HMA manufacturing process and the decrease in energy usage, obviously, has also the result of reducing energy costs and the use of natural resources (fuel) [24].

In Figure 10, the energy range typically used to dry and then to heat is illustrated for the different technologies and it is expressed in MMBTU-Million British Thermal Units per ton of product, representing the fuel usage.

Indeed, each fuel type has a proper calorific value (energy value), which is the amount of energy released as heat when this fuel undergoes complete combustion, expresses as energy/mass of fuel (i.e. MMBtu/ton) or energy/volume of fuel.

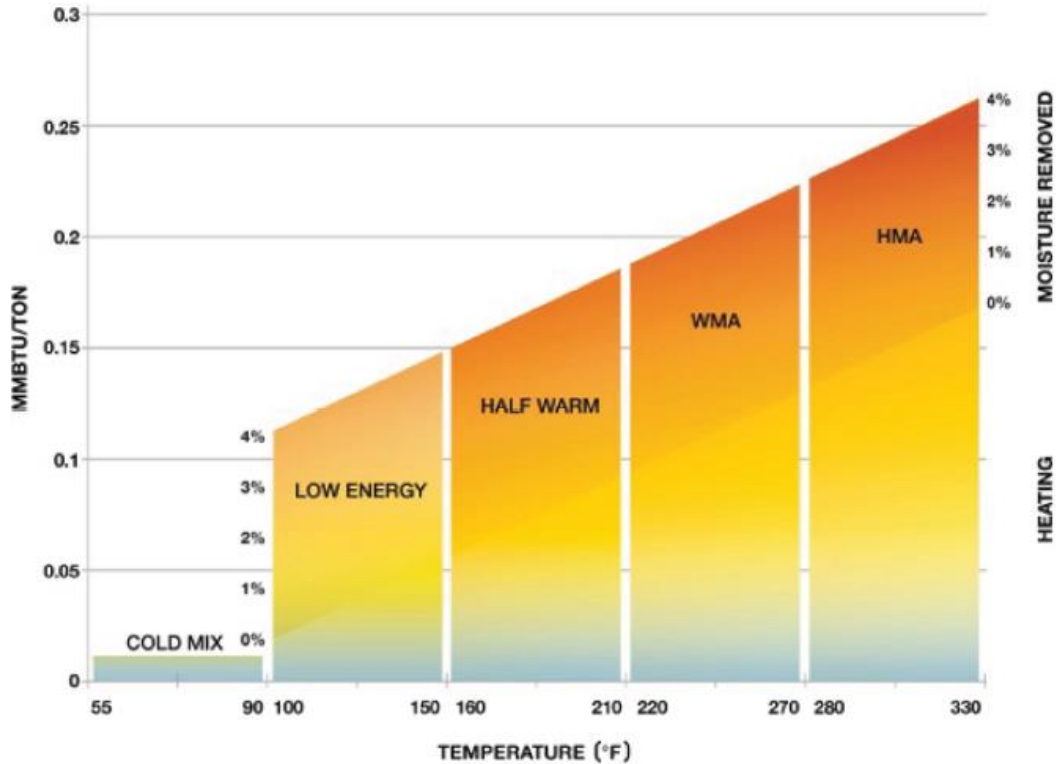


Figure 10. Energy use for the aggregate drying and heating [24].

However, precision of fuel measurements may be questionable for a number of reasons, and potential errors for direct measures (tank sticks and gas meters) could be identified by comparing measured fuel usage to fuel usage calculated from stoichiometric plant stack emissions.

In general, the potential reduction in temperature varies even by the specific WMA technology applied and furthermore, the energy consumption depends also on several factors such as aggregate moisture content, production rate, mixing temperature, excess of air for combustion process. For example, it must be considered that aggregate stockpiles at ambient temperature are characterized by different moisture contents which vary depending on how they are produced and stored, and on the local weather conditions.

Of course, it may have a relevant effect on fuel consumption: indeed, a significant amount of energy is required to dry aggregate and turn the water into steam. Specifically, the temperature of the aggregate cannot increase above 100°C (212°F) until the aggregate is dry. Once the aggregate is dry, continued heating will bring it to the mixing temperature.

Moreover, when selecting the production temperatures there are also some technical data to consider, such as the flow through the plant and associated motor amperage. However, because of the influence of these several factors, it can be difficult in general properly adjusting the burner to maintain the optimum fuel to air ratio: if excess fuel is introduced to increase production rate, there could be the risk of incomplete combustion, with consequences on emissions and waste of fuel.

Properly tuned burners will affect fuel combustion and the resulting emissions at lower settings, allowing for a higher % of reduction [7].

3.1.1 Case study and estimation of the potential fuel saving

The **project 9-47 A**, related to the NCHRP REPORT 779 of the *National Cooperative Highway Research Program*, has conducted a detailed research about the importance of comparing the energy consumption of different WMA technologies to HMA one [25].

The objective of this case study was to obtain plant energy data from 6 projects (Table 3) by considering different plant configurations, environmental conditions and WMA technologies.

Date	Project Location	Plant Site and Description	Mixes
July 19–21, 2010	County Road 513, Rapid River, Michigan	Escanaba, Michigan, uninsulated parallel-flow drum	HMA, Advera, Evotherm 3G
Sept. 14–15, 2010	Calumet Avenue, Munster, Indiana	Griffith, Indiana, insulated counter-flow dryer	HMA, Gencor Foam, Evotherm 3G, Heritage Wax
Oct. 19–22, 2010	Little Neck Parkway, New York City, New York	New York City, New York, batch plant with mini drum uninsulated dryer	HMA, Cecabase RT, SonneWarmix, BituTech PER
April 19–20, 2010	US-12 near Walla Walla, Washington	Walla Walla, Washington, portable plant, uninsulated parallel-flow drum	HMA, Maxam Foam
June 21–22, 2010	I-66 eastbound, near Centreville, Virginia	Centreville, Virginia, double barrel, counter-flow	HMA, Astec Foam
Aug. 11–12, 2010	Montana Route 322, south of Baker, Montana	Baker, Montana, partially insulated parallel-flow drum	HMA, Evotherm DAT

Table 3. Project information summary [25].

For NCHRP Project 9-47A, data collection documents were developed to collect information on plant energy usage during production, including the above variable factors.

The participating contractors were requested to tune their plants' burners before producing asphalt for this project and, for 3 of the 6 plants, even stack emissions (steady-state operating period) tests were performed.

Moreover, the 6 different plants involved use different fuels for heating and drying aggregate:

- Walla Walla (WASHINGTON): natural gas;

- Centreville (VIRGINIA): natural gas;
- Rapid River (MICHIGAN): RFO (Reclaimed motor oil fuel);
- Baker (MONTANA): LP (Liquid propane);
- Griffith Plant (INDIANA): natural gas;
- New York (NEW YORK): natural gas.

However, the precision of direct fuel measurements was questionable: for example, in the case of natural gas use, data collection was based on gas meter readings and it was found that those commercial meters only update periodically and therefore they are not the best solution for accurate measurement of fuel usage during cumulative production. For this reason, an alternative method to determine average heat input was investigated, involving a stoichiometric calculation from stack emission tests but applied only in Michigan, Indiana and New York plants. In these tests, flow rate and composition of the exhaust gases have been recorded continuously for two 1-hour runs for each WMA and HMA control mixture. Specifically, these stack gas data enabled back-calculation of average heat input using the so called “EPA’s Method 19 *F factor*”. The EPA developed F factors for commercially available fuels to calculate the stoichiometric volume of exhaust gases generated by burning one MMBTU of fuel.

The equation used for these calculations in order to define the fuel firing rate is the following [25]:

$$\text{Fuel Usage} = \frac{60 * Q * \left(\frac{20.9 - O_2\%}{20.9} \right)}{F} = [\text{MMBTU/hr}] \quad (1)$$

with:

F = Volume of combustion products per unit of heat content = [dscfm/MMBTU]

Q = Average stack gas dry volumetric flow rate (dscfm) at standard temperature and pressure

60 = Converts flow per minute to flow per hour [min/hr]

20.9 = Standard O₂% of air

O₂% = percent stack O₂ by volume, dry basis [%]

$\left(\frac{20.9-0.2\%}{20.9}\right)$ = Correction factor to remove excess air and calculate resulting stoichiometric volume.

Table 4 summarizes fuel usage based on direct measurement of fuel consumption and the corresponding cumulative production, except for Virginia HMA because of an error in reading the gas meter. Moreover, the stoichiometric calculation from stack emission tests applied in Michigan, Indiana and New York plants are listed in the same table.

It's important to take notice of the correction to apply in terms of *aggregate moisture content*: for example, one of the potential errors in determining fuel usage is illustrated with the fact that the Michigan Advera and Evotherm 3G mixes were produced at the same average temperature, but the Evotherm moisture content was 0.2 % higher, which would tend to increase fuel usage. However, the fuel usage calculated for Evotherm production seemed to be even 17% less than the one calculated for the Advera WMA. So, to make meaningful comparisons between the WMA and HMA, the WMA fuel usage data were corrected for the difference between the HMA and WMA aggregate moisture content at each site with a corrective coefficient.

Actually, it's important to remember that the Equation 1 used for the stoichiometric calculation was applied only in 3 sites: Michigan, Indiana and New York [25]. Moreover, in Indiana case study, the readings about HMA and Heritage Wax stack velocity were taken only at the end of the run: therefore, these stoichiometric calculations of fuel usage are suspect and probably erroneous.

Site	Plant ¹	Mix	Avg. Stock-pile Moist. (%)	Avg. Prod. Rate (TPH)	Avg. Mix Temp. (°F)	Avg. Stack Temp. (°F)	Fuel Use, (MMBtu/ton)	Fuel Use, (MMBtu/ton)	Stoichiometric Fuel Use (MMBtu/ton)	Agg. Moisture Correction (MMBtu/ton)	MMBtu/ton Corrected for Agg. Moisture	Delta (MMBtu/ton)	Delta (Btu/°F)
Washington	Uninsulated PF drum	HMA	2.6%	316	325	339	0.278	NA	NA	NA	0.278		
		Maxam foam	3.0%	310	285	295	0.218	NA	0.009	0.009	0.209	0.069	1728
Virginia	Double barrel	HMA	2.3%	270	318	218	NA	NA	NA	NA	NA		
		Astec foam	2.1%	221	288	191	0.203	NA	-0.005	NA	0.208		
Michigan	Uninsulated PF drum	HMA	3.6%	310	300	330	0.271	0.285²	NA	NA	0.285		
		Advera	3.9%	323	269	292	0.225	0.237	0.007	0.007	0.230	0.055	1769
		Evotherm 3G	4.1%	320	269	296	0.187	0.241	0.011	0.011	0.230	0.055	1788
Montana	Partially insulated PF drum	HMA	1.3%	370	298	249	0.157	NA	NA	NA	0.157		
		Evotherm DAT	1.5%	378	252	238	0.137	NA	NA	0.005	0.132	0.025	534
Indiana	Insulated CF dryer	HMA	3.2%	292	300	242	0.226²	0.201³	NA	NA	0.226		
		Gencor foam	3.5%	300	277	232	0.209	0.223	0.007	0.007	0.202	0.024	1037
		Evotherm 3G	3.8%	300	256	221	0.212	0.207³	0.014	0.014	0.198	0.028	630
		Heritage wax	3.8%	279	268	227	0.201	0.159	0.014	0.014	0.187	0.039	1210
New York	Batch-mini drum uninsulated dryer	HMA	3.1%	271	332	284	0.260	0.299²	NA	NA	0.299		
		Cecabase RT	3.4%	244	240	213	0.236	0.235	0.007	0.007	0.228	0.071	770
		SonneWarmix	2.4%	267	252	195	0.216	0.198	-0.016	-0.016	0.214	0.085	1063
		BituTech PER	3.6%	268	253	202	0.253	0.211	0.011	0.011	0.200	0.099	1258

¹ PF: parallel-flow; CF: counter-flow.

² Values in **bold** used two measures of fuel usage.

³ Stack velocity measurements only taken at end of each stack emissions run; stoichiometric fuel usage believed to be erroneous.

Table 4. Fuel usage in 6 projects [25].

From these results, the average fuel usage for the **HMA** production based on five projects (Virginia is wrong, so not considered) is **0.249 MMBtu/ton**. On the other side, it's possible to see that for the **WMA**, the average consumption is about **0.194 MMBtu/ton**; it means

that the *fuel saving* is **0.055 MMBtu/ton**, or approximately of **22.1 %**, considering an average temperature reduction of 27°C (48°F). This value compares well to the typical range reported in literature [7, 8].

Starting from the fuel saving measured, the next step is looking for a way to estimate it, to be able to use this estimation method in generic situations. From a theoretical point of view, fuel savings should be equal to the difference between WMA and HMA mix temperatures (in °F) multiplied by the average specific heat of the aggregate, assumed to be more or less 0.24 Btu/lb/°F [25].

However, in this way, considering again the temperature difference of 48°F (=27 °C), it will result in 0.0230 MMBtu/ton savings (only 9.3%):

being: **1 lb = 0.0005 ton**

Energy saving: $(0.24 \text{ Btu}/0.0005 \text{ ton}/^{\circ}\text{F}) * 48^{\circ}\text{F} = 23040 \text{ Btu}/\text{ton} = \mathbf{0.0230 \text{ MMBtu}/\text{ton}}$

The question is how to account for the additional 13 % in fuel savings to breakeven the 0.055 MMBtu/ton measured through the 6 projects, which corresponds to 22.1% of saving.

Actually, 0.055 MMBtu/ton is higher than predictions based on thermodynamic material properties (i.e. aggregate specific heat), and this appear to be related to the fact that the heat radiated through the plant's dryer shell and ductwork into the surrounding environment, instead of being transferred to the mix, was larger than expected.

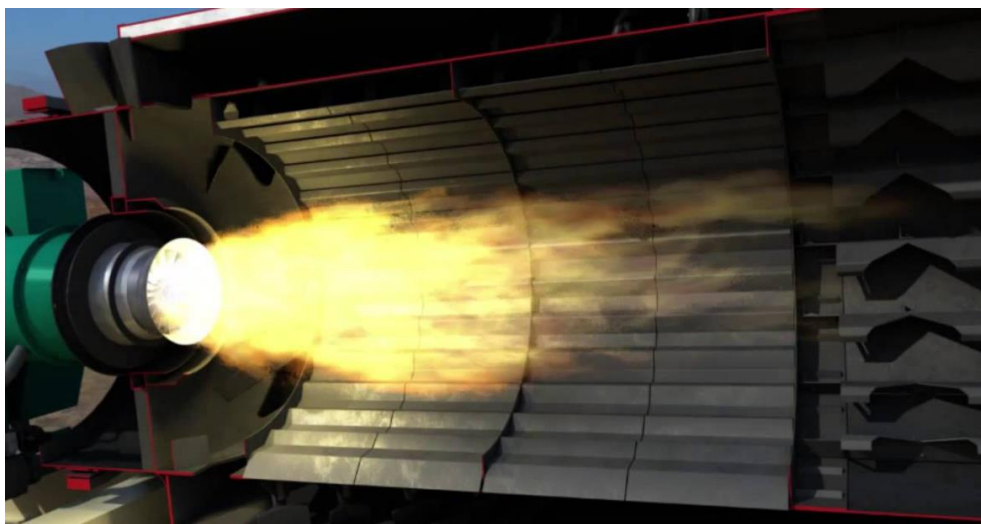


Figure 11. Flame in the dryer shell (Sit.3).

Specifically, thermal energy generated to produce the mixture is consumed by drying and heating aggregate, heating stack gases and casing losses. Casing losses are thermal energy used to heat plant iron and then radiated to the atmosphere, rather than being used for the aggregate.

So, on the basis of the energy audits for WMA and HMA projects in this 9-47A case study [25], energy savings for Warm Mix Asphalt production were found to be reasonably approximated by the following empirical general relationship:

$$ENERGYSAVINGS = 1100 \text{ Btu} / ^\circ\text{F} / \text{ton}$$

[It means that for each °F reduced in the production of the asphalt mixture, 1100 Btu of energy will be saved]

Indeed, using this empirical relationship and considering the temperature difference 48°F, it can be obtained a value really close to the savings measured (0,055 MMBtu/ton):

$$\text{Energy Savings } (\Delta T = 48^\circ\text{F}) = 1100 \text{ Btu}/^\circ\text{F}/\text{ton} * 48^\circ\text{F} = 52\,900 \text{ Btu}/\text{ton} = 0.053 \text{ MMBtu}/\text{ton}$$

It's interesting to see in practice that WMA production temperatures when using water-injection foaming technologies are about 25°F (15 °C) lower than those for conventional HMA using the same mix design; while, in case of additive-type (chemical or organic) WMA the reduction could be even more than 50°F.

So, considering that most asphalt plants in the USA use either natural gas or recycled fuel oil (RFO) for burner, we can also try to estimate a potential economic saving per ton of mixture produced using WMA technology.

In case of RFO, it is known that the energy density is about 137 000 Btu/gal, with a recent cost of 2\$/gal [25]; while, using natural gas, the price is swinging, so it can be used 4.30 \$/MMBtu.

Example of calculations.

- Economic saving for water-injection type WMA using **RFO**:
1 100 Btu/°F/ton * 25°F = 27 500 Btu/ton
(27 500 Btu/ton / 137 000 Btu/gal) * 2\$/gal = 0,39 \$/ton = **0,35 €/ton**;

- Economic saving for additive type WMA using **RFO**:
 $1\ 100\ \text{Btu}/^\circ\text{F}/\text{ton} * 50^\circ\text{F} = 55\ 000\ \text{Btu}/\text{ton}$
 $(55\ 000\ \text{Btu}/\text{ton} / 137\ 000\ \text{Btu}/\text{gal}) * 2\$/\text{gal} = 0,80\ \$/\text{ton} = \mathbf{0,71\ \text{€}/\text{ton}}$;
- Economic saving for water-injection type WMA using **Natural gas**:
 $1100\ \text{Btu}/^\circ\text{F}/\text{ton} * 25^\circ\text{F} = 27\ 500\ \text{Btu}/\text{ton}$
 $0,0275\ \text{MMBtu}/\text{ton} * 4.30\ \$/\text{MMBtu} = 0,12\ \$/\text{ton} = \mathbf{0,14\ \text{€}/\text{ton}}$;
- Economic saving for additive type WMA using **Natural gas**:
 $1100\ \text{Btu}/^\circ\text{F}/\text{ton} * 50^\circ\text{F} = 55\ 000\ \text{Btu}/\text{ton}$
 $0,055\ \text{MMBtu}/\text{ton} * 4.30\ \$/\text{MMBtu} = 0,24\ \$/\text{ton} = \mathbf{0,21\ \text{€}/\text{ton}}$;

So, to recap, from the case study of Project 9-47A it is obtained that, knowing the ΔT between HMA and WMA, the energy saving can be approximately estimated as related to 1100 Btu/°F/ton: it means that using the WMA technology, in case of applying an average $\Delta T = 50^\circ\text{F}$ (28°C), it will be possible to achieve an average energy saving of about 0.055 MMBtu/ton, compared to HMA technology, corresponding to an average profit of about 0,46 €/ton (depending on fuel type).

This example of calculations shows the possibility to have an economic gain from the energy consumption standpoint; however, the use of additive or zeolites for foaming bitumen may result in higher costs, reducing the possible profit linked to the fuel saving [24].

3.2 Stack emissions

The measurement of emissions during asphalt production can be complex and expensive, so limited guidance is available for this purpose.

The National Cooperative Highway Research Program NCHRP funded project 9-47A to update the protocol for documenting also emissions reduction of WMA during plant operations [25]. However, available data on emissions during WMA production using this

protocol are very limited [26]. In support, the U.S. Army Engineer Research and Development Center – ERDC was tasked to collect information from literature and from projects aiming at documenting this reduction.

Reducing emissions through the use of warm mix technology depends on several factors, including temperature reduction, type of fuel used during production, the plant's design and operation, aggregate moisture content and use of recycled asphalt pavement (RAP).



Figure 12. Stack emissions from Asphalt Plant (Sit.5).

As seen before, in the drying and heating process, the aggregate is dried in a rotating, slightly inclined, direct-fired drum dryer. The interior of the dryer is equipped with flights that veil the aggregate through the hot exhaust as the dryer rotates.

The dryer emissions can be defined as “*process emissions*”, which are combustion emissions generated during the production process. In general, in this step, combustion (NO_x, SO₂, CO₂, CO, VOCs) and non-combustion emissions (H₂O, PM₁₀, VOCs, PAHs) are generated; however, the extent of these emissions will depend on the combustion process and equipment used, and type of fuel. For example, in drum dryers the amount of PM₁₀ generated is usually lower than within batch dryers; however, the asphalt is heated to high

temperatures for a longer period of time in drum plants, so organic emissions are generally greater than in batch ones [26].

Summing up what is present in Literature dealing with stack emissions data, **Table 5** summarize the results coming from different studies in terms of Emission Reduction (%) comparing the WMA with the HMA impact.

Emission	Emission Reduction (%) ^{a,b}				
	Davidson and Pedlow (2007)	D'Angelo et al. (2008)	Middleton and Forflylow (2008)	Hurley et al. (2010)	Frank et al. (2011)
CO ₂	17	15-40	11	5	19
SO ₂	-17	18-35	-14	— ^c	55
NO _x	20	18-70	8	14	18
VOC	— ^c	19-50	— ^c	-313	-17
CO	20	10-30	10	— ^c	19

^a Negative values indicate an increase in emissions when WMA was used

^b Average reductions from multiple test sites

^c Data were not provided

Table 5. Stack emissions reductions present in Literature [26].

Concerning carbon monoxide CO, carbon dioxide CO₂ and nitrogen oxides NO_x, it can be observed a more or less homogeneous reduction using WMA, differently from SO₂, where in certain cases there will be also an increase in concentration using the warm technology. The authors indicated that it could be even connected with testing variability. Equally important is to focus on VOC: D'Angelo et al. (2008) showed a clear reduction in the range of 19-50 %; while in other case studies was recorded an increase in concentration of organic matter by 313% during WMA production, compared to HMA. The authors believed unburned fuel was released into the dryer increasing the amount of VOCs emitted [26].

In general, as shown in Table 5, it is difficult to find a clear relationship in literature to define the benefit of WMA technology in terms of emissions reduction, because of the possible several factors (equipment used, fuel type, maintenance and burner tuning...) that could influence the potential emission over and above the temperature applied.

So, the target of the next paragraph will be to find a way to approximately estimate and compare the impact of the WMA emissions to the HMA one, during this heating step considering the use of Natural gas as fuel type to feed the burner.

3.2.1 Stackemissions estimation

As mentioned in the previous chapters and paragraphs, the dryer impact is mainly related to the combustion emissions in the order of magnitude. It means that the heating temperatures to achieve and the type of fuel involved will make the difference in terms of pollution at the asphalt plant [26]. Specifically, the production of GHGs such as CO₂, primarily result from fuel combustion with a sort of linear relationship [22, 26, 39], as shown in Figure 13, where both the data collected in literature and the data gathered in the NCHRP Project 9-47A are reported. It means that using WMA technology, reducing the mixing temperatures, it will result in a decrease in carbon dioxide emissions accordingly to the increasing fuel savings.

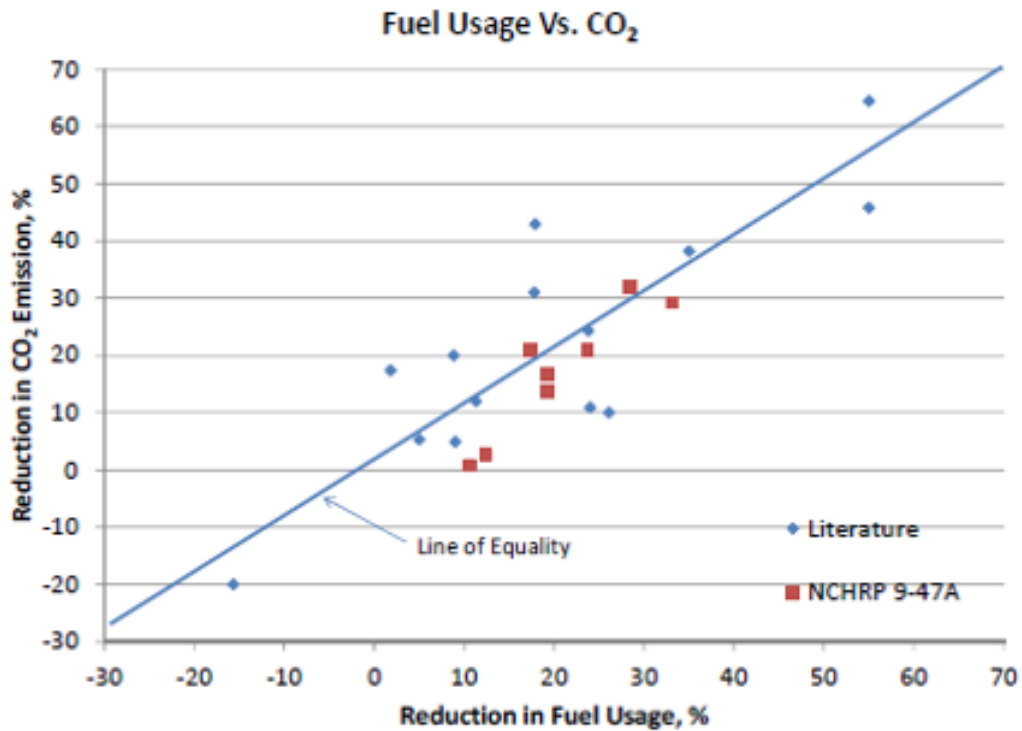


Figure 13. Reduction in fuel usage VS Reduction in CO₂ emissions [22].

For instance, in China, an interesting case study shows the significant impact of the asphalt pavement construction on the environment, energy use and greenhouse gas emissions [27]. Specifically, the results say that the production in plant implies the highest slice of GHG production: the 54,01 % of the total amount, dealing with the full cycle of operations (Raw materials production, mixture production in plant, transportation, laying down phase, compaction). The second highest GHG emission phase (43,18 %) is the production of raw materials, not considered in this project thesis.

In the first part of this paragraph, it will be defined a way to estimate the different impact of GHG emissions dealing respectively with WMA and HMA.

The first step of the calculation is to find a reliable source of carbon emission factors. The different possible database has already been introduced in Section 3.2.2, and, concerning Greenhouse Gas emissions, the most useful should be the collection by the *Intergovernmental Panel on Climate Change* (IPCC) [28]. In *Chapter 2-Stationary Combustion* of this Database, all the emission factors regarding CO₂, CH₄, N₂O are gathered, considering the possible fuel involved. As shown in Table 6, these factors are expressed in mg/MJ, according to the fuel type.

	Coal	Fuel oil	Diesel/petrol	Asphalt	Natural gas
CO ₂	94,600	77,400	74,100	80,700	56,100
CH ₄	1	3	3	3	1
N ₂ O	1.5	0.6	0.6	0.6	0.1

Table 6. GHG emission factor according to fuel type [mg/MJ] [28].

For example, considering the use of **Natural Gas**, the *Emission Factors EF* of GHGs produced are respectively:

- **56100 mg CO₂/MJ** of energy involved;
- **1 mg CH₄/MJ** of energy involved;
- **0,1 mg N₂O/MJ** of energy involved.

For what concerns the energy necessary respectively for the production of 1 ton of HMA and WMA, it will be considered again the case study well analysed in Section 6.1.1 about Energy Saving estimation, from NCHRP Project 9-47A [25]. Taking into account an average

temperature difference of about 27°C (=48°F) between HMA and WMA technology, the average fuel usage for asphalt concrete production is resulted to be:

- 0,249 MMBtu/ton for *Hot Mix Asphalt*;
- 0,194 MMBtu/ton for *Warm Mix Asphalt*.

Therefore, being **1 MMBTU = 1,000,000 BTU = 1055.06 MJ**, it will be:

- Average Energy Usage for **HMA**: 0.249 MMBTU/ton = **262.71 MJ/ton**;
- Average Energy Usage for **WMA**: 0.194 MMBTU/ton = **204.68 MJ/ton**.

So, it can be easily calculated the amount of pollutant emissions released per ton of asphalt produced (g/ton), by multiplying the average respective energy usage to produce WMA or HMA (MJ/ton) and the EF (mg GHG/MJ) related to the use of Natural Gas as fuel type shown in Table 6.

Example of calculation:

- **CO₂**

Natural Gas emission CO₂ EF: 56 100 mg CO₂/MJ

Average Production Energy for **HMA**: **262,71 MJ/ton**

Average Production Energy for **WMA**: **204,68 MJ/ton**

CO₂ HMA = 262,71*56 100*10⁻⁶ = 14,75 KgCO₂/ton

CO₂ WMA = 204,68*56 100*10⁻⁶ = 11,48 KgCO₂/ton

The calculation method is the same for all the parameters; the results, to compare the GHG emission impact concerning these two technologies, are gathered in **Table 7**:

Emissions	HMA	WMA	Δ emission
CO₂	14,75 Kg/ton	11,48 Kg/ton	3,22 Kg/ton
CH₄	0,26 g/ton	0,21 g/ton	58 mg/ton
N₂O	26,27 mg/ton	20,47 mg/ton	5,80 mg/ton

Table 7. Impact of GHGs emissions - HMA vs WMA

Looking at the carbon dioxide CO₂, key-parameter dealing with these Greenhouse gases, it can be observed the heavy impact and also the difference in using the warm technology: producing conventional hot mix asphalt, it will be emitted about 15 kgCO₂/ton, while considering a temperature reduction of 27 °C (48°F), the environmental benefit will be counted in over 3 kgCO₂/ton of mixture, that corresponds to about 21,9%, in perfect agreement to what is commonly found in Literature [29]. In general, it is known that the reduction of greenhouse gas emissions is in the same magnitude as the energy gains: it means that they are strictly related to the temperature applied [39].

Regarding the CH₄ and N₂O emission rates, their production is low, but not negligible from an environmental standpoint as their GWP is really relevant, as shown in Section 3.1.

Since the other airborne emissions related to this combustion process (such as CO, NO_x, SO₂, VOCs) are not present in the *IPCC EFDB*, the *AP-42 Compilation of Air Pollutant Emissions Factors*, published by U.S. EPA, was considered as it contains emission factors even for specific industry sectors or similar emitting sources. Specifically, in the Chapter 11.1-12 of the 1995 edition of AP-42, a very interesting table with some emission factors (kg/ton) for conventional HMA production is present (Table 8), by comparing Batch mix plants and Drum ones, specifying the use of different dryer combustion fuels (Natural gas, oil) [4]. However, the values in this table are only representative of the Hot mixture production and useful just to compare the impact using different fuel type: except for carbon monoxide CO, the other emissions are characterized by lower values using natural gas instead of oil. Thus, these interesting factors cannot be used to analyse the temperature impact to compare Warm to Hot technology application.

Process	Emission Factor (kg/tonne) ^{a,c}			
	CO	NO _x	SO ₂	VOCs ^d
Batch mix asphalt plants:				
Natural gas-fired dryer	0.17	0.013	0.0025	0.0072
Oil-fired dryer	0.035	0.084	0.12	0.02
Drum asphalt plants^b:				
Natural gas-fired dryer	0.028	0.015	0.0017	0.022
Oil-fired dryer	0.018	0.038	0.028	0.03

Source: USEPA Document AP-42 Ch. 11.1-12 (1995).

^a Factor units are kg of pollutant emitted per tonne of asphalt produced.

^b Includes both parallel and counter flow asphalt plants.

^c All emission factors have an uncertainty rating of E.

^d Converted from TOC (expressed as methane) in USEPA AP 42, Ch. 11.1-12. By using an average ratio of (MW of VOC) to (wt of carbon in that VOC) = 1.15. (Derived from the State of California Air Resources Board, *Identification of Volatile Organic Compound Species Profiles*, ARB Speciation Manual, Volume 1, August 1991, Table II, VOC Species Profiles 715 and 716.

Table 8. Typical dryer emission factors for HMA production [4].

For this kind of purpose, the European Environment Agency-EEA provided the most useful database. The drying and heating process is defined as “combustion process with contact”, because the flame is in contact with the material in the dryer. In the EEA Guidebook 2019, the asphalt manufacture is coded as NFR 1.A.2 (corresponding to the SNAPcode 030313 of the Corinair). The average values of some Emission Factors, expressed as g/GJ, are collected in **Table 9** as a function of natural gas as gaseous fuel used [19].

	Code	Name			
NFR Source Category	1.A.2	Manufacturing industries and construction			
Fuel	Gaseous Fuels				
Not applicable					
Not estimated	NH ₃ , PCBs, HCB				
Pollutant	Value	Unit	95% confidence interval		Reference
			Lower	Upper	
NO _x	74	g/GJ	46	103	See note
CO	29	g/GJ	21	48	See note
NMVOG	23	g/GJ	14	33	See note
SO _x	0.67	g/GJ	0.40	0.94	See note
TSP	0.78	g/GJ	0.47	1.09	See note
PM ₁₀	0.78	g/GJ	0.47	1.09	See note
PM _{2.5}	0.78	g/GJ	0.47	1.09	See note
BC	4.0	% of PM _{2.5}	2.1	7	See note
Pb	0.011	mg/GJ	0.006	0.022	See note
Cd	0.0009	mg/GJ	0.0003	0.0011	See note
Hg	0.54	mg/GJ	0.26	1.0	See note
As	0.10	mg/GJ	0.05	0.19	See note
Cr	0.013	mg/GJ	0.007	0.026	See note
Cu	0.0026	mg/GJ	0.0013	0.0051	See note
Ni	0.013	mg/GJ	0.006	0.026	See note
Se	0.058	mg/GJ	0.015	0.058	See note
Zn	0.73	mg/GJ	0.36	1.5	See note
PCDD/F	0.52	ng I-TEQ/GJ	0.25	1.3	See note
Benzo(a)pyrene	0.72	µg/GJ	0.20	1.9	See note

Table 9. Emission Factors for combustion using gaseous fuel - EEA Guidebook 2019 [19].

On this basis, it's possible to estimate the stack emissions related to the most significant pollutants (NO_x, NMVOG, CO, PM, SO_x), comparing the impact of WMA and HMA. The method will be the same applied in the case of GHGs calculations.

Therefore, being **1 MMBTU = 1000000 BTU = 1.055 GJ**, it will be:

- Average Energy Usage for **HMA**: 0.249 MMBTU/ton = **0.263 GJ/ton**;
- Average Energy Usage for **WMA**: 0.194 MMBTU/ton = **0.205 GJ/ton**.

So, it can be easily calculated the amount of pollutant emissions released per ton of asphalt produced (g/ton), by multiplying together the average respective energy usage to produce WMA or HMA (GJ/ton) and the EF (g/GJ) found in Table 9. The calculation results are gathered in Table 10.

Emissions	HMA	WMA	Δ emission
NO _x	19,46 g/ton	15,17 g/ton	4,29 g/ton
NM VOC	6,05 g/ton	4,71 g/ton	1,34 g/ton
CO	7,62 g/ton	5,95 g/ton	1,67 g/ton
PM	0,41 g/ton	0,32 g/ton	0,09 g/ton
SO _x	0,17 g/ton	0,14 g/ton	0,03 g/ton

Table 10. Impact of Airborne Emissions – HMA vs WMA.

So, also in this case, in the fourth column of the table is calculated the difference of pollutant emission in g/ton. The drawback of this kind of estimation is based on the fact that it is just connected with an “ideal” combustion process, because these emissions are strictly related to the fuel type. It means that reducing the consumption of fuel by about **20%**, it has been obtained a directly proportional reduction % in emissions: nevertheless, this reduction obviously is not considering all the others uncontrolled variables such as the equipment involved, aggregate moisture variability, uncombusted fuel effects, burner tuning, maintenance operations and so on. However, these calculations are reliable and significant enough to show the direct effects of reducing production temperatures, adopting different asphalt mixture technologies.

In Chapter 9 of this theses, real stack emissions data from a case study will be analysed, to show the influence of all those uncontrolled factors compared to an ideal combustion process.

4- Load-out and Silo filling impact

Dealing with the main sources of *EFDB-Emission Factors DataBase* mentioned before, for the kind of target to achieve in this chapter has been chosen the *Compilation of Air Pollutant Emissions Factors*, AP-42 [4]. In its Chapter 11, “*Mineral products Industry*”, a lot of detailed information and explanation about HMA plants emissions impact are gathered and, differently from the other sources, emission factors for load-out and silo filling emissions as function of the temperature, fundamental for the comparison between HMA and WMA, can be found.

This section summarizes the review of emission test reports that address emissions from two different asphalt plants concerning some facility operations. The objective is to explain how the general Predictive Emission Factor Equations have been obtained, starting from two specific case studies.

4.1 Case Studies: “Plant C” & “Plant D”

Starting from the analyses of two real case studies involving different asphalt plants, some Predictive Emission Factor Equations have been developed:

- Plant C – *Drum-mix asphalt plant* located in Los Angeles, California [30];
- Plant D – *Batch asphalt plant* located in Barre, Massachusetts [31].

These tests analyses were sponsored by EPA and were based on a cooperative effort between EPA, citizen’s groups, State agencies and industry.

The test program quantified emissions from the HMA mixing by considering load-out operations, silo filling operations and “Background Emissions”:

- *Silo Filling Operations*: HMA produced is transported by bucket elevator into temporary storage silos that serve as a holding station between production and the loading into trucks.

- *Load-out Operations*: the hot mixture is dropped from the storage silos into the transportation trucks, within a load-out tunnel. To complete the loading phase, it takes about 20-30 seconds for a drum mix plant, whereas about 5-10 minutes in case of a batch plant;
- *Background Emissions*: represent a measure of the contribution of truck emissions to the measured load-out ones. The analysis of these emissions was performed using two trucks that crossed over the load-out area, while no loading was occurring, determining the background emissions by diesel truck exhaust.

The **Asphalt Plant C** is a *continuous Drum-mix HMA* production facility located in Los Angeles, California with an asphalt production capacity is 650 tons/hr. During the test, it ranged from 370 tons/hr to 630 tons/hr. Two kinds of asphalts, different in terms of dynamic viscosity values (AR-4000 (softer) and AR-8000) are used. The average asphalt binder content was 5.0 %, with a range from 4.9 to 5.2 %, and it is used a percentage equal to 30% of RAP.

In this plant, load-out, silo filling operations and “Background Emissions” were measured. Source sampling was performed in the load-out tunnel exhaust duct and silo exhaust duct to determine the concentrations and mass emission rates. It must be considered for both load-out and silo filling operations, also the presence of some deposition emissions connected to the asphalt fumes condensing on the plant facility surfaces, such as the TED (Tunnel exhaust duct).

On the load-out process were performed a total of three test runs, while a fourth test was performed to measure just background emissions from trucks without considering asphalt loading.

To the emission factors from this case study were assigned an A rating thanks to the high reliability of scrutiny related to the development of the test program [4].

The **Asphalt Plant D** is a *Batch mix facility* located in Barre, Massachusetts: the maximum production capacity of HMA is 255 tons/hr, but the normal average production is about 150 tons/hr. The average asphalt binder content is about 5.2 %, ranged from 4.5 % to 5.7 %.

The 95% of asphalt concrete produced includes 10 % of RAP.

In this test program, only the emissions from load-out operations were performed (three test runs even in this case), consisting in measurements of mainly TOC and PM coming from the dropping of the hot mixture into the transportation trucks. Even in this case, some deposition emissions must be considered. Specifically, to conduct this emissions test, a total temporary enclosure was constructed around the load-out station with entrance and exit doors that were closed during truck operations: obviously, this kind of enclosure satisfies the EPA methods requirement.

Due to the high level of scrutiny included in the development of the test program, implementation and production of the test report, to the emission factors from this case study were assigned an A rating [31].

4.2 Development of Predictive Emission Factor Equations

This Section will focus on the origin of these *equations* with the aim of looking into and checking their applicability in case of different boundary conditions (temperature, material volatility) and different locations (USA, Italy).

As mentioned before, the predictive equations will be related to *Load-out* and *Silo filling operations*, and the resulting values will be expressed as **lb** (of pollutant)/**ton** of HMA produced.

Indeed, this is an American study and the units of measure used in this chapter are not from the International System (IS), so, it is important to take notice of changing them to assess and compare the results after the application of the equations.

These analyses concern:

- Total PM;
- Organic PM;
- TOC-Total Organic Carbon;
- CO-Carbon Monoxide.

In this Section, the reports of the analyses of Plant C and Plant D will be considered, by presenting all the collected emission data about the test-runs. Starting from these data, the resulting predictive emission factor equations were obtained distinctly for Plant C and D with the objective of comparing and combining them in order to deduce general equations that allow to estimate Emission Factors also for other case studies.

In the entire discussion concerning these equations, it is important focusing on two key-role parameters:

- V = Asphalt Volatility (% by weight), as determined by ASTM Method D2872-88 “Effects of Heat and Air on a Moving Film of Asphalt (Rolling Thin Film Oven Test – RTFOT)”;
- T = HMA mixing temperature;

The *asphalt volatility* V is a parameter typical of the kind of asphalt used and can vary from -0,5% to 0,5%. It is representative of the loss-on-heating as a result of the ASTM Method D2872-88 Test, which allows to simulate the change of asphalt properties during the hot mixing procedure, considering a temperature of about 325°F (163°C) \pm 25°F. The range considered (-0,5% \div 0,5%) is explained by the fact that samples with a very low percentage of volatile components usually will exhibit a mass gain ($V > 0$), while samples with a high percentage of volatile components usually exhibit a mass loss ($V < 0$). Indeed, the mass change (% by weight) is considered a measure of the asphalt volatility.

The **temperature** T is a key-factor for the prediction of asphalt plant emissions as processes characterized by higher temperatures will release also a higher quantity of air emissions. Moreover, as seen before, the use of lower temperatures will reduce not only the energy consumption but even the CO₂ emissions [4].

It is important to take notice of some remarkable differences between the Plant C and Plant D conditions, which emphasize the need to require some adjustments before making a comparison and a reliable combination of their respective results:

1. Plant C is a drum-mix asphalt plant in which both Load-out and Silo filling operational emissions have been considered; while, Plant D is a batch asphalt plant, in which just the load-out operational emissions have been collected;
2. the reported load-out emissions data from plant C includes also one test about the quantification of emissions due to truck operations without asphalt loading (*Backgroundrun*);
3. the asphalt volatility of the two case studies is different, meaning that two different types of bitumen were investigated, affecting the degree of environmental discharge and worker fumes exposure in a relatively different way [32].

It means that all these factors had to be adjusted to some consistent values to be compared [33].

4.2.1 Load-out emissions from Plant C and Plant D

In both Plant C and D, 3 test runs have been done to collect emissions data: each of these tests were characterized by 3 different temperatures. Obviously, decreasing this temperature was possible to observe also a resulting reduction of the asphalt volatility.

The three test runs about the **Plant C** were performed with the following values of temperature and corresponding volatility:

- 1- T= 321°F; V= -0,362%;
- 2- T= 316°F; V= -0,322%;
- 3- T= 291°F; V= -0,284%

Concerning the **Plant D**, the performance of these test runs was characterized by:

- 1- T= 306,7°F; V= -0,204%;
- 2- T= 325,1°F; V= -0,246%;
- 3- T= 326,7°F; V= -0,261%.

So, these two plants worked at different temperatures and with different asphalt volatility: for this reason, it is very important performing some adjustments to arrive to load-out and silo filling emissions at standardized temperature and volatility.

The data collected through these emissions analyses are presented in the respective reports regarding Plant C [30] and D [31].

Plant C

Dealing with the Plant C, the concentrations of pollutants are expressed in *grains of particulate matter per dry standard cubic feet of exhaust air (gr/dscf)* at 20°C and 1 atm, in *parts-per-million (ppm)*, in *parts-per billion (ppb)* and in *parts-per-billion of volume dry (ppbvd)*, and then converted into emission factors expressed in *pounds per ton* of asphalt loaded (lb/ton).

Specifically, in case of the only Plant C, there are 4 test runs: indeed, the fourth test regards the background emissions, which are the ones coming from the operation of diesel trucks, as explained before.

In the meanwhile, during the load-out and background tests, also *Capture Efficiency-CE* measurement was performed: it represents the weight per unit time of a certain substance entering a capture system and delivered to a control device, divided by the weight per unit time of the total substance generated by a source. This value is expressed as a percentage (%). The CE% is a very important parameter in terms of measurements reliability, allowing for adjustment of the data collected: in fact, in Plant C the load-out tunnel enclosure did not meet EPA method criteria for total enclosures, so this CE testing were required and performed throughout each of the four test runs, obtaining respectively 64%, 65%, 54% and 45%.

In the following Tables the results of the load-out and background tests related to Plant C have been summarized: capture efficiency-corrected (CE-corrected) emissions data are already incorporated in the emission calculations as it can be observed as “*Corrected for CE%*” [30].

Respectively, in **Table 11** are reported all the emissions data concerning Particulate based Load-out emissions, while in **Table 12** all emissions data about Volatile Organic Load-out emissions related to the Plant C.

	Run 1 Loading		Run 2 Loading		Run 3 Loading		Background Run	
Asphalt Loss on Heating (RTFOT, % by weight)	-0.362		-0.322		-0.284			
Load out Temperature (°F)	321		316		291			
90% Lower Confidence Limit Capture Efficiency	0.64		0.65		0.54			0.45
	Corrected For CE%		Corrected For CE%		Corrected For CE%		As Measured	Corrected For CE%
	gr/dscf	#/ton	gr/dscf	#/ton	gr/dscf	#/ton	gr/dscf	gr/dscf
Particulate^b								
PM	1.92e-03	3.56e-04	1.14e-03	2.65e-04	1.59e-03	2.05e-04	7.93e-04	1.76e-03
MCEM	1.68e-03	3.12e-04	3.50e-04	8.16e-05	5.05e-04	6.52e-05	3.78e-04	8.40e-04
PAH								
			ppbvd	#/ton	ppbvd	#/ton	ppbvd	ppbvd
Acenaphthene			2.51e-01	1.57e-07	3.28e-01	1.24e-07	1.79e-02	3.97e-02
Acenaphthylene			2.62e-02	1.64e-08	3.87e-02	1.46e-08	2.60e-03	5.78e-03
Anthracene			8.20e-02	5.95e-08	6.24e-02	2.73e-08	6.19e-03	1.38e-02
Benzo(a)anthracene			1.39e-02	1.29e-08	1.37e-02	7.70e-09	3.29e-04	7.32e-04
Benzo(b)fluoranthene			5.45e-03	5.60e-09	5.21e-03	3.23e-09	3.58e-04	7.95e-04
Benzo(k)fluoranthene			1.60e-03	1.64e-09	1.36e-03	8.44e-10	ND ^c	ND ^c
Benzo(g,h,i)perylene			1.37e-03	1.54e-09	1.21e-03	8.19e-10	1.36e-04	3.02e-04
Benzo(a)pyrene			1.63e-03	1.68e-09	1.40e-03	8.69e-10	ND ^c	ND ^c
Benzo(e)pyrene			6.13e-03	6.30e-09	4.81e-03	2.98e-09	2.58e-04	5.73e-04
Chrysene			7.90e-02	7.35e-08	8.42e-02	4.72e-08	6.81e-03	1.51e-02
Dibenz(a,h)anthracene			4.94e-04	5.60e-10	ND ^c	ND ^c	ND ^c	ND ^c
Fluoranthene			5.10e-02	4.20e-08	4.65e-02	2.31e-08	7.44e-03	1.65e-02
Fluorene			1.09e+00	7.35e-07	5.96e-01	2.43e-07	4.83e-02	1.07e-01
Indeno(1,2,3-cd)pyrene			5.92e-04	7.00e-10	ND ^c	ND ^c	ND ^c	ND ^c
2-Methylnaphthalene			2.30e+00	1.33e-06	3.34e+00	1.17e-06	9.17e-02	2.04e-01
Naphthalene			1.27e+00	6.65e-07	1.89e+00	5.96e-07	ND ^c	ND ^c
Perylene			1.81e-02	1.85e-08	1.12e-02	6.95e-09	ND ^c	ND ^c
Phenanthrene			1.01e+00	7.35e-07	7.38e-01	3.23e-07	1.13e-01	2.51e-01
Pyrene			1.36e-01	1.12e-07	1.35e-01	6.70e-08	1.49e-02	3.31e-02

ND = Measured data below detection limits

Table 11. Reported Particulate based Load-out emissions. (PLANT C)

	Corrected For CE%		Corrected For CE%		Corrected For CE%		As Measured	Corrected For CE%
	ppm	#/ton	ppm	#/ton	ppm	#/ton	ppm	ppm
THC	1.11e+01	1.72e-03	1.18e+01	2.00e-03	1.43e+01	1.70e-03	0.83 ^b	1.84
Methane	5.00e+00	2.81e-04	4.77e+00	3.08e-04	6.11e+00	2.04e-04	3	6.67
Acetone (ppb)	1.28e+01	2.51e-06	6.62e+00	1.68e-06	2.31e+00	3.57e-07	2.00e+00	4.43e+00
CO	3.59e+00	3.44e-04	1.26e+01	1.43e-03	1.24e+01	7.41e-04	3.5	7.78
Ethylene	1.72e-01	1.72e-05	ND ^c	ND ^c	2.59e-01	1.56e-05	ND ^c	ND ^c
VOHAPS	ppb	#/ton	ppb	#/ton	ppb	#/ton	ppb	ppb
Benzene (M 0030)	6.82e+00	1.80e-06	4.39e+00	1.50e-06	3.33e+00	6.95e-07	1.07e+00	2.37e+00
Benzene (M 18)	ND ^c	ND ^c	1.06e+01	3.31e-06	ND ^c	ND ^c	ND ^c	ND ^c
Bromomethane	1.83e+00	5.89e-07	5.00e-01	2.08e-07	3.85e-02	9.76e-09	9.15e-02	2.03e-01
2-Butanone	5.61e+00	1.37e-06	5.06e+00	1.60e-06	1.68e+00	3.24e-07	2.67e-01	5.93e-01
Carbon Disulfide	4.66e-01	1.20e-07	1.57e+00	5.23e-07	5.00e-01	1.02e-07	ND ^c	ND ^c
Chloroethane	7.70e-02	1.68e-08	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c
Chloroform	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	1.90e-02	4.22e-02
Chloromethane	3.34e+00	5.72e-07	2.04e+00	4.51e-07	1.06e+00	1.43e-07	3.74e-01	8.31e-01
Cumene (M 0030)	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c
Cumene (M 18)	2.17e+01	9.03e-06	1.51e+01	7.29e-06	ND ^c	ND ^c	ND ^c	ND ^c
Ethylbenzene (M 0030)	2.47e+00	8.89e-07	6.79e-01	3.16e-07	1.45e+00	4.12e-07	1.46e-01	3.24e-01
Ethylbenzene (M 18)	5.02e+01	1.84e-05	6.22e+01	2.65e-05	2.24e+01	5.83e-06	1.55e+01	3.43e+01
Formaldehyde	ND ^c	ND ^c	ND ^c	ND ^c	4.44e-02	2.78e-06	ND ^c	ND ^c
n-Hexane (M 0030)	3.19e+00	9.32e-07	3.48e+00	1.31e-06	3.26e+00	7.50e-07	3.90e-01	8.67e-01
Hexane (M 18)	1.84e+01	5.50e-06	3.43e+01	1.19e-05	ND ^c	ND ^c	ND ^c	ND ^c
Isooctane	ND ^c	ND ^c	3.33e-01	1.67e-07	7.69e-02	2.34e-08	1.06e-01	2.35e-01
Methylene Chloride	7.23e+00	2.08e-06	3.34e+00	1.24e-06	1.19e+01	2.70e-06	1.21e+01	2.68e+01
MTBE	1.53e-01	4.57e-08	6.60e-01	2.55e-07	5.40e-01	1.27e-07	7.07e-01	1.57e+00
Styrene	ND ^c	ND ^c	4.60e-01	2.10e-07	7.17e-01	1.99e-07	1.45e-01	3.22e-01
	ppm	#/ton	ppm	#/ton	ppm	#/ton	ppm	ppm
Tetrachloromethane	3.94e-01	2.21e-07	3.19e-01	2.31e-07	2.91e-01	1.29e-07	8.65e-02	1.92e-01
Toluene (M 0030)	9.83e+00	3.07e-06	3.60e+00	1.45e-06	5.00e+00	1.23e-06	1.33e+00	2.95e+00
Toluene (M 18)	2.67e+01	8.52e-06	4.48e+01	1.66e-05	2.12e+01	4.79e-06	1.05e+01	2.33e+01
1,1,1-Trichloroethane	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	3.40e-02	7.55e-02
Trichloromethane	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	ND ^c	2.87e-03	6.39e-03
Trichlorofluoromethane	8.78e-02	4.09e-08	1.11e-01	6.67e-08	1.49e-01	5.47e-08	7.42e-02	1.65e-01
m-/p-Xylene (M 0030)	1.44e+01	5.18e-06	3.84e+00	1.78e-06	7.08e+00	2.01e-06	4.09e-01	9.09e-01
m-Xylene (M 18)	1.09e+01	4.00e-06	1.04e+01	4.43e-06	ND ^c	ND ^c	ND ^c	ND ^c
p-Xylene (M 18)	3.25e+01	1.19e-05	2.03e+01	8.64e-06	ND ^c	ND ^c	ND ^c	ND ^c
Formaldehyde	ND ^c	ND ^c	ND ^c	ND ^c	4.44e-02	2.78e-06	ND ^c	ND ^c
o-Xylene (M 0030)	4.46e+00	1.60e-06	1.10e+00	5.12e-07	2.57e+00	7.28e-07	1.74e-01	3.87e-01
o-Xylene (M 18)	1.22e+01	4.47e-06	8.57e+00	3.65e-06	ND ^c	ND ^c	ND ^c	ND ^c

ND = Measured data below detection limits

Table 12. Reported Volatile Organic Load-out emissions. (PLANT C)

One of the most reliable method to cope with this problem would be subtracting the CE-corrected Background emissions from the CE-corrected emissions measured in the 3 test

runs during the Load-out operations. However, in this way, there is the risk of having many negative values. So, to provide a more reliable method, the “as-measured” background concentration (= not CE-corrected) must be subtracted from the CE-corrected concentrations and then multiply everything by the ratio of the capture-efficiency corrected emission factor EF_{prod} (second column of each run, expressed in lb/ton) to the capture efficiency-corrected concentration. In this way, using **Equation 2**, it is possible to obtain the *Background-corrected emission factors* EF_{corr} for each one of the three test runs, and then they can be reconverted into the respective emission concentration in gr/dscf.

$$EF_{corr} = [(C_{prod}) - (C_{back})] \times \frac{EF_{prod}}{C_{prod}} \quad (2)$$

EF_{corr} = background corrected emission factor (lb/ton)

C_{prod} = Capture efficiency-corrected production concentration (gr/dscf)

C_{back} = as-measured background concentration (gr/dscf)

EF_{prod} = Capture efficiency corrected emission factor (lb/ton)

This background adjustment method resulted in a low estimate for the background emissions, and, therefore, emissions factors for load-out will be conservatively high. These results are shown in **Table 13** for Background-corrected Particulate based Load-out emissions, and in **Table 14** for Background-corrected Volatile Organic Load-out emissions, both concerning the Plant C [30].

	Run 1 Loading		Run 2 Loading		Run 3 Loading	
Asphalt Loss on Heating (RTFOT, % by weight)	-0.362		-0.322		-0.284	
Load out Temperature (°F)	321		316		291	
Particulate	gr/dscf	#/ton	gr/dscf	#/ton	gr/dscf	#/ton
PM	1.30e-03	2.41e-04	3.44e-04	8.01e-05	7.98e-04	1.03e-04
MCEM	1.30e-03	2.41e-04	-2.83e-05	0.00e+00 ^a	1.27e-04	1.64e-05
PAH			ppbvd	#/ton	ppbvd	#/ton
Acenaphthene			2.33e-01	1.46e-07	3.10e-01	1.17e-07
Acenaphthylene			2.36e-02	1.48e-08	3.61e-02	1.37e-08
Anthracene			7.58e-02	5.50e-08	5.62e-02	2.46e-08
Benzo(a)anthracene			1.36e-02	1.26e-08	1.34e-02	7.51e-09
Benzo(b)fluoranthene			5.09e-03	5.23e-09	4.85e-03	3.01e-09
Benzo(k)fluoranthene			1.60e-03	1.64e-09	1.36e-03	8.44e-10
Benzo(g,h,i)perylene			1.23e-03	1.39e-09	1.07e-03	7.27e-10
Benzo(a)pyrene			1.63e-03	1.68e-09	1.40e-03	8.69e-10
Benzo(e)pyrene			5.87e-03	6.03e-09	4.55e-03	2.82e-09
Chrysene			7.22e-02	6.71e-08	7.74e-02	4.34e-08
Dibenz(a,h)anthracene			4.94e-04	5.60e-10	ND ^b	ND ^b
Fluoranthene			4.35e-02	3.58e-08	3.91e-02	1.94e-08
Fluorene			1.04e+00	7.02e-07	5.48e-01	2.24e-07
Indeno(1,2,3-cd)pyrene			5.92e-04	7.00e-10	ND ^b	ND ^b
2-Methylnaphthalene			2.20e+00	1.28e-06	3.25e+00	1.13e-06
Naphthalene			1.27e+00	6.65e-07	1.89e+00	5.96e-07
Perylene			1.81e-02	1.85e-08	1.12e-02	6.95e-09
Phenanthrene			9.00e-01	6.53e-07	6.25e-01	2.74e-07
Pyrene			1.21e-01	9.97e-08	1.20e-01	5.97e-08

ND = Measured data below detection limits

Table 13. Background-corrected Particulate based Load-out emissions. (PLANT C)

	ppm	#/ton	ppm	#/ton	ppm	#/ton
THC	1.03e+01	1.59e-03	1.10e+01	1.86e-03	1.34e+01	1.60e-03
Methane	2.00e+00	1.13e-04	1.77e+00	1.14e-04	3.11e+00	1.04e-04
CO	9.37e-02	8.97e-06	9.12e+00	1.03e-03	8.91e+00	5.32e-04
Acetone (ppb)	1.08e+01	2.12e-06	4.62e+00	1.17e-06	3.10e-01	4.80e-08
Ethylene	1.72e-01	1.72e-05	ND ^a	ND ^a	2.59e-01	1.56e-05
VOHAPS	ppb	#/ton	ppb	#/ton	ppb	#/ton
Benzene (M 0030)	5.75e+00	1.52e-06	3.32e+00	1.13e-06	2.27e+00	4.72e-07
Benzene (M 18)	ND ^a	ND ^a	1.06e+01	3.31e-06	ND ^a	ND ^a
Bromomethane	1.74e+00	5.59e-07	4.08e-01	1.70e-07	-5.29e-02	0.00e+00 ^b
2-Butanone	5.34e+00	1.30e-06	4.80e+00	1.51e-06	1.42e+00	2.73e-07
Carbon Disulfide	4.66e-01	1.20e-07	1.57e+00	5.23e-07	5.00e-01	1.02e-07
Chloroethane	7.70e-02	1.68e-08	ND ^a	ND ^a	ND ^a	ND ^a
Chloroform	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a
Chloromethane	2.97e+00	5.08e-07	1.67e+00	3.68e-07	6.84e-01	9.21e-08
Cumene (M 0030)	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a
Cumene (M 18)	2.17e+01	9.03e-06	1.51e+01	7.29e-06	ND ^a	ND ^a
Ethylbenzene (M 0030)	2.33e+00	8.37e-07	5.33e-01	2.48e-07	1.31e+00	3.71e-07
Ethylbenzene (M 18)	3.48e+01	1.28e-05	4.68e+01	1.99e-05	6.92e+00	1.80e-06
Formaldehyde (ppm)	ND ^a	ND ^a	ND ^a	ND ^a	4.44e-02	2.78e-06
n-Hexane (M 0030)	2.80e+00	8.19e-07	3.09e+00	1.17e-06	2.87e+00	6.60e-07
Hexane (M 18)	1.84e+01	5.50e-06	3.43e+01	1.19e-05	ND ^a	ND ^a
Isooctane	ND ^a	0.00e+00 ^b	2.28e-01	1.14e-07	-2.89e-02	0.00e+00 ^b
Methylene Chloride	-4.83e+00	0.00e+00 ^b	-8.73e+00	0.00e+00 ^b	-1.32e-01	0.00e+00 ^b
MTBE	-5.54e-01	0.00e+00 ^b	-4.62e-02	0.00e+00 ^b	-1.67e-01	0.00e+00 ^b
Styrene	ND ^a	ND ^a	3.15e-01	1.44e-07	5.72e-01	1.59e-07
Tetrachloromethane	3.07e-01	1.73e-07	2.32e-01	1.69e-07	2.05e-01	9.06e-08
VOHAPS	ppb	#/ton	ppb	#/ton	ppb	#/ton
Toluene (M 0030)	8.50e+00	2.65e-06	2.27e+00	9.17e-07	3.67e+00	9.02e-07
Toluene (M 18)	1.63e+01	5.19e-06	3.44e+01	1.27e-05	1.07e+01	2.42e-06
1,1,1-Tri chloroethane	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a
Trichloromethane	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a	ND ^a
Trichlorofluoromethane	1.36e-02	6.33e-09	3.66e-02	2.20e-08	7.49e-02	2.75e-08
m-/p-Xylene (M 0030)	1.40e+01	5.03e-06	3.43e+00	1.59e-06	6.67e+00	1.89e-06
m-Xylene (M 18)	1.09e+01	4.00e-06	1.04e+01	4.43e-06	ND ^a	0.00e+00 ^b
p-Xylene (M 18)	3.25e+01	1.19e-05	2.03e+01	8.64e-06	ND ^a	ND ^a
o-Xylene (M 0030)	4.28e+00	1.54e-06	9.27e-01	4.31e-07	2.40e+00	6.79e-07
o-Xylene (M 18)	1.22e+01	4.47e-06	8.57e+00	3.65e-06	ND ^a	ND ^a

ND = Measured data below detection limits

Table 14. Background-corrected Volatile Organic Load-out emissions. (PLANT C)

Plant D

Dealing with the Plant D, the results about Load-out emissions are shown in **Table 15**, expressed directly as emission factors in lb/ton. In this case, the test runs are just related to the measurement of *Particulate Matter-PM*, *Methylene Chloride Extractable Matter-MCEM* and *Total Hydrocarbon Emissions-THC*. Concerning the PM and MCEM, some measurements were made to estimate the matter deposition on the inside walls of the enclosure; however, differently from Plant C case study, here were not gathered data about background emissions. Moreover, in Plant D there was no need for applying capture efficiency correction CE% to the test runs, because the enclosure concerning load-out operations was designed and constructed to satisfy the requirement of a “temporary total enclosure” as specified in EPA methods.

	Run 1	Run 2	Run 3	Deposition
	10/5/98	10/6/98	10/7/98	
Asphalt Loss on Heating (RTFOT)	-0.204	-0.246	-0.261	
Load out Temperature (F)	306.7	325.1	326.7	
	lb/ton	lb/ton	lb/ton	lb/ton
Particulate Matter (PM)	1.37e-03	1.78e-03	7.27e-04	3.37e-05 ^b
MCEM	2.46e-04	1.50e-04	1.27e-04	3.58e-06
THC (ppm)	1.53e-03	1.71e-03	1.71e-03	

Table 15. Reported Load-out emissions. (PLANT D)

4.2.2 Adjustment for Asphalt Volatility and Temperature

Volatility

Concerning the Asphalt Volatility V, samples of asphalt binder used during each test run were collected and their mass loss-on-heating was determined according to the ASTM D2872-88 (RTFOT).

Specifically, organic air emissions from asphalt should be considered directly proportional to the loss-on-heating measured by the test.

To determine a common RTFOT value to use as a default in situations where no historical information is available, a survey of laboratories of a limited number of State departments of transportation was performed.

Information on the rolling thin film tests for Plant C and D, and for selected States were obtained in 1999 and are presented in **Table 16**.

State	Number of Samples	Average loss on heating (ASTM D2872-88) (percent mass change)	Standard Deviation
Massachusetts	44	-0.232	0.124
Plant D - MA	3	-0.237	0.030
Connecticut	29	-0.355	0.147
North Carolina	226	-0.227	0.160
Michigan	32	-0.272	0.173
Minnesota	438	-0.440	0.289
Plant C - CA	13	-0.330	0.040

Table 16. Average loss-on-heating from selected States

To face this variability a default value has been established, which encourages the use of site-specific data: “V = -0,5” was used [33].

So, after correcting for capture efficiency and truck background emissions, data from Plant C and Plant D must be adjusted to this default value before being compared and combined. Emission factors (related to the individual test runs) were normalized to a -0,5% loss-on-heating value, obtaining the “EF_{V adj}” by multiplying the background-corrected Emission Factor EF_{corr} by the ratio of -0,5 % to the asphalt volatility measured during the tests.

$$EF_{V \text{ adj}} = EF_{\text{corr}} * \left(-\frac{0,5}{V}\right) \quad (3)$$

EF_{V adj} = Emission Factor adjusted to default volatility [lb/ton];

EF_{corr} = Background-corrected Emission Factor [lb/ton];

V = Asphalt volatility [%];

Temperature

Dealing with the effects of the temperature differences, it's clear that the temperature has an important impact on organic emissions connected with asphalt binder.

During both Plant C & D emissions tests, these effects have been studied even through the ASTM D2872-88 test, in which the temperatures changes were performed in a range of 25°F above and below the reference temperature of 325°F. The results are presented in Table 17:

Temperature (deg F)	Date	Loss on Heating (% by RTFOT)	Date	Loss on Heating (% by RTFOT)
	California Test Data		Massachusetts Test Data	
300	07/24/98	-0.216	10/05/99	-0.089
	07/25/98	-0.200	10/06/99	-0.105
	07/27/98	-0.142	10/07/99	-0.109
	07/28/98	-0.171		
325	07/24/98	-0.369	10/05/99	-0.216
	07/25/98	-0.311	10/06/99	-0.206
	07/27/98	-0.286	10/07/99	-0.218
	07/28/98	-0.292		
350	07/24/98	-0.686	10/05/99	-0.400
	07/25/98	-0.611	10/06/99	-0.395
	07/27/98	-0.498	10/07/99	-0.380
	07/28/98	-0.510		

Table 17. Loss-on-heating data collected as a function of the testing temperature

As expected, the highest values of Asphalt Volatility (Loss on Heating %) are related to the highest temperature performed (350°F). Moreover, the impact of the temperature on the loss-on-heating is stronger in the case study of the Plant C (California) than in Plant D (Massachusetts), because of the different kind of asphalt binder involved.

The next step considers the achievement of a clear relationship that can relate the loss-on-heating and the temperature through the constants of the Antoine equation which is a class of semi-empirical correlations describing the relation between the vapor pressure and the temperature of substances. Indeed, the vapor pressure is an indication of the evaporation rate

of a substance: a higher vapour pressure means a higher volatility of a certain substance. All this reasoning comes from the Clausius-Clapeyron relation, which is based on the concept of the linear relationship between the natural logarithm of the vapor pressure and the inverse of the absolute temperature (K). So, the Antoine equation is derived from the Clausius-Clapeyron relation.

Using the data of the previous **Table 17** (loss-on-heating data collected as a function of the changing temperature in plants C and D), the constants to describe this relationship for the distinct asphalts used during the tests were empirically developed. So, using data respectively from plant C and D, it is possible to relate the temperature to the loss-on-heating by using the following two equations:

- Plant C:
$$\text{Loss} = -e^{((t+460)*0,0231-19,28)} \quad (4)$$

- Plant D:
$$\text{Loss} = -e^{((t+460)*0,0271-22,93)} \quad (5)$$

(t = temperature expressed in °F)

During stakeholder meetings to discuss the collection and analysis of this data, it was suggested that, following the “Best Practices” brochure published by the Asphalt Pavement Environmental Council, good paving practices dictate that production temperature over 325°F should be avoided. In addition, in terms of boundary conditions for these equations, are included also some suggestion about the common temperatures range for the mixing of HMA: the midpoint plant **mixing temperatures range** may go from **264°F (127°C) to 315°F (157°C)** [33].

In general, concerning the two case studies, the main idea was to maximize the emissions by asking both the plants to increase the mixing temperature as much as possible to combine the results later. However, it was not easy; so, the equations developed from the laboratory testing provide the possibility to normalize the emissions to the temperature of 325°F, by multiplying the EF_{corr} by the ratio of the loss-on-heating at 325°F to the estimated loss at the temperature measured during the tests.

$$EF_{T \text{ adj}} = EF_{\text{corr}} * \frac{e^{((325+460)*0,0231-19,28)}}{e^{((t+460)*0,0231-19,28)}} \quad \text{Plant C]} \quad (6)$$

$$EF_{T \text{ adj}} = EF * \frac{e^{((325+460)*0,0271-22,93)}}{e^{((t+460)*0,0271-22,93)}} \quad \text{Plant D]} \quad (7)$$

$EF_{T \text{ adj}}$ = Emission Factor adjusted to the temperature of 325°F [lb/ton];

EF_{corr} = Background-corrected Emission Factor [lb/ton];

EF = Measured Emission Factor with no corrections (Plant D) [lb/ton];

t = Temperature measured during the tests [°F]

It must be observed that for the Plant C the adjustment to a consistent volatility and temperature was performed on EF_{corr} , after correcting for both capture efficiency and background emissions; while, for Plant D the adjustment was applied directly to the measured emissions EF , as no correction for capture efficiency or truck background emissions was required.

So, to sum up, the emission factors for the plants are normalized to a temperature of 325°C and to a volatility of -0,5 %, using respectively the **Equation 8** and **9**, for Plant C and D:

$$EF_{Std} = EF_{Corr} \left(\frac{-0.5}{V} \right) \left[\frac{e^{((0.0231) (325 + 460) - 19.28)}}{e^{((0.0231) (T + 460) - 19.28)}} \right] \quad (8)$$

Equation. EF at standard condition of 325°F and V=-0,5 % (Plant C)

$$EF_{Std} = EF \left(\frac{-0.5}{V} \right) \left[\frac{e^{((0.0271) (325 + 460) - 22.93)}}{e^{((0.0271) (T + 460) - 22.93)}} \right] \quad (9)$$

Equation. EF at standard condition of 325°F and V=-0,5 % (Plant D)

EF_{Std} = Emission Factor at standard conditions of 0,5 % loss-on-heating and 325°F;

EF_{corr} = Background-corrected Emission Factor in Plant C [lb/ton];

EF = Emission Factor as measured in Plant D [lb/ton];

V = Asphalt volatility determined by ASTM Method D2872-88 [%];

T = Asphalt temperature [°F].

In **Table 18** and **Table 19** the “temperature and volatility-adjusted” emissions for Plant C are collected, expressed as lb/ton; while, in **Table 20** it is possible to observe these adjusted emissions, in lb/ton, concerning Plant D [33].

	Run 1	Run 2	Run 3	Average
Asphalt Loss on Heating (RIFOT, % by weight)	-0.362	-0.322	-0.284	
Load out Temperature (°F)	321	316	291	
90% Lower Confidence Limit Capture Efficiency	0.64	0.65	0.54	
Particulate^a				
	#/ton	#/ton	#/ton	#/ton
PM	3.66e-04	8.01e-05	1.50e-04	1.99e-04
MCEM	3.66e-04	0.00e+00	6.34e-05	1.43e-04
PAH				
		#/ton	#/ton	#/ton
Acenaphthene		2.79e-07	4.53e-07	3.66e-07
Acenaphthylene		2.83e-08	5.28e-08	4.05e-08
Anthracene		1.05e-07	9.50e-08	1.00e-07
Benzo(a)anthracene		2.42e-08	2.90e-08	2.66e-08
Benzo(b)fluoranthene		1.00e-08	1.16e-08	1.08e-08
Benzo(k)fluoranthene		3.14e-09	3.26e-09	3.20e-09
Benzo(g,h,i)perylene		2.65e-09	2.81e-09	2.73e-09
Benzo(a)pyrene		3.21e-09	3.36e-09	3.28e-09
Benzo(e)pyrene		1.15e-08	1.09e-08	1.12e-08
Chrysene		1.28e-07	1.67e-07	1.48e-07
Dibenz(a,h)anthracene		1.07e-09	ND ^b	5.35e-10
Fluoranthene		6.85e-08	7.49e-08	7.17e-08
Fluorene		1.34e-06	8.63e-07	1.10e-06
Indeno(1,2,3-cd)pyrene		1.34e-09	ND ^b	6.69e-10
2-Methylnaphthalene		2.44e-06	4.38e-06	3.41e-06
Naphthalene		1.27e-06	2.30e-06	1.79e-06
Perylene		3.54e-08	2.68e-08	3.11e-08
Phenanthrene		1.25e-06	1.06e-06	1.15e-06
Pyrene		1.91e-07	2.30e-07	2.10e-07

Table 18. *Temperature and Volatility adjusted Particulate based Load-out emissions. (PLANT C)*

	#/ton	#/ton	#/ton	#/ton
THC ^a	2.41e-03	3.56e-03	6.20e-03	4.05e-03
Methane	1.70e-04	2.18e-04	4.00e-04	2.63e-04
Acetone	3.21e-06	2.25e-06	1.85e-07	1.88e-06
CO	1.36e-05	1.98e-03	2.05e-03	1.35e-03
Ethylene	2.60e-05	ND ^b	6.01e-05	2.87e-05
TOC ^c				4.06e-03
VOHAPS	#/ton	#/ton	#/ton	#/ton
Benzene (M 0030)	2.31e-06	2.17e-06	1.82e-06	
Benzene (M 18)	ND	6.33e-06	ND	
Benzene (Average)				2.10e-06
Bromomethane	8.47e-07	3.25e-07	0.00e+00 ^d	3.91e-07
2-Butanone	1.98e-06	2.89e-06	1.05e-06	1.97e-06
Carbon Disulfide	1.82e-07	1.00e-06	3.92e-07	5.25e-07
Chloroethane	2.55e-08	ND	ND	8.50e-09
Chloroform	ND	ND	ND	
Chloromethane	7.70e-07	7.04e-07	3.56e-07	6.10e-07
Cumene (M 0030)	ND	ND	ND	
Cumene (M 18)	1.37e-05	1.39e-05	ND	
Cumene (Average)				4.60e-06
Ethylbenzene (M 0030)	1.27e-06	4.74e-07	1.43e-06	
Ethylbenzene (M 18)	1.93e-05	3.81e-05	6.96e-06	
Ethylbenzene (Average)				1.13e-05
Formaldehyde	ND	ND	1.07e-05	3.58e-06
n-Hexane (M 0030)	1.24e-06	2.23e-06	2.55e-06	
Hexane (M 18)	8.33e-06	2.27e-05	ND	
Hexane (Average)				6.17e-06
Isooctane	ND	2.17e-07	0.00e+00	7.25e-08
VOHAPS	#/ton	#/ton	#/ton	#/ton
Methylene Chloride	0.00e+00	0.00e+00	0.00e+00	0.00e+00
MTBE	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Styrene	ND	2.75e-07	6.13e-07	2.96e-07
Tetrachloromethane	2.61e-07	3.22e-07	3.50e-07	3.11e-07
Toluene (M 0030)	4.02e-06	1.75e-06	3.48e-06	
Toluene (M 18)	7.86e-06	2.43e-05	9.35e-06	
Toluene (Average)				8.46e-06
1,1,1-Tri chloroethane	ND	ND	ND	0.00e+00
Trichloromethane	ND	ND	ND	0.00e+00
Trichlorofluoromethane	9.58e-09	4.21e-08	1.06e-07	5.26e-08
m-/p-Xylene (M 0030)	7.63e-06	3.05e-06	7.29e-06	
m-Xylene (M 18)	6.06e-06	8.47e-06	ND	
p-Xylene (M 18)	1.81e-05	1.65e-05	ND	
m-/p-Xylene (Average)				1.66e-05
o-Xylene (M 0030)	2.33e-06	8.23e-07	2.62e-06	
o-Xylene (M 18)	6.78e-06	6.98e-06	ND	
o-Xylene (Average)				3.26e-06

Table 19. *Temperature and Volatility adjusted Volatile Organic Load-out emissions. (PLANT C)*

[lb/ton]	Deposition of particulate (Plant C)
PM inorganic	1.25*10 ⁻⁴
MCEM (PM organic)	1.93*10 ⁻⁵

Table 20. Deposition of particulate during Load-out operations in Plant C [30]

	Run 1	Run 2	Run 3		
	10/5/98	10/6/98	10/7/98	Average	
Asphalt Loss on Heating (RTFOT, % by weight)	-0.204	-0.246	-0.261	-0.237	
Load out Temperature (F)	306.7	325.1	326.7	319.5	
					Deposition
	lb/ton	lb/ton	lb/ton	lb/ton	lb/ton
Particulate Matter (PM)	2.11e-03	1.93e-03	8.33e-04	1.62e-03	3.89e-05 ^a
MCEM	9.90e-04	3.04e-04	2.33e-04	5.09e-04	8.77e-06
THC (ppm)	6.16e-03	3.47e-03	3.13e-03	4.25e-03	

Table 21. Temperature and Volatility adjusted Load-out emissions. (PLANT D)

After these adjustments, the data have been compared to determine whether to present separate or one average value concerning Load-out Emission Factors for batch and drum-mix plants. The following considerations were made.

Dealing with particulate matter, it is very important to consider also the deposition fraction of emissions, connected with a measure of asphalt fumes condensing on load-out facility surfaces (i.e. Tunnel Exhaust Duct – TED). The primary difference between the 2 plants is that the inorganic PM emissions from plant D are higher (almost ten times) than the same emissions in Plant C: this is probably due to the added dust emissions from the gravel paving surface, since no background run was performed at Plant D. *Inorganic PM* was not adjusted for asphalt temperature or volatility because this non-MCEM PM represents stone dust or road dust emissions, not affected by asphalt conditions (temperature and volatility). In general, it is: $Inorganic\ PM = Total\ PM - MCEM\ (organic\ PM)$. Of course, in each calculation it must be considered the sum between both deposition and corrected sampled emissions. The inorganic PM deposition for Plant C (Tab.20) was 1.25*10⁻⁴ lb/ton, while the Inorganic PM by sampling (difference between average PM and MCEM from the

previous **Table 18**) is $5,6 \cdot 10^{-5}$ lb/ton. So, the resulting Total Inorganic PM from Plant C is: $1,25 \cdot 10^{-4} + 5,6 \cdot 10^{-5} = 1,81 \cdot 10^{-4}$ lb/ton. Concerning the Plant D, the inorganic PM deposition (**Tab.21**) was $3,01 \cdot 10^{-5}$ lb/ton, while the sampled one was given by the difference between the average Total PM and MCEM (**Tab.21**), obtaining $1,12 \cdot 10^{-3}$ lb/ton. So, the resulting total inorganic PM from Plant D is given by: $3,01 \cdot 10^{-5} + 1,12 \cdot 10^{-3} = 1,15 \cdot 10^{-3}$ lb/ton. Nevertheless, since in Plant D a background test was not performed, this datum was affected by a higher uncertainty and thus the Load-out predictive equations was developed by considering directly the value **$1,81 \cdot 10^{-4}$ lb/ton** as **inorganic PM**.

It is also important to know that the load-out operation in a batch plant involves a longer time (5-10 minutes) compared to what happens in a drum-mix plant (20-30 seconds). This is demonstrated by the fact that the Methylene Chloride Extractable Matter (MCEM) PM from Plant D (batch plant) is about four times the emissions from Plant C (drum-mix plant). Moreover, also the deposition MCEM fraction must be considered and they are respectively equal to $1,93 \cdot 10^{-5}$ lb/ton and $8,77 \cdot 10^{-6}$ lb/ton for Plant C (**Tab.20**) and D (**Tab.21**). The resulting temperature and volatility-adjusted *Total MCEM PM emission factors* are given by the sum between the deposition and sampled MCEM:

- MCEM (*Plant C*) deposited (**Tab.20**) + sampled (**Tab.18**) = $1,93 \cdot 10^{-5} + 1,43 \cdot 10^{-4} = 1,62 \cdot 10^{-4}$ lb/ton;
- MCEM (*Plant D*) deposited (**Tab.21**) + sampled (**Tab.21**) = $8,77 \cdot 10^{-6} + 5,09 \cdot 10^{-4} = 5,18 \cdot 10^{-4}$ lb/ton.

So, the average between these two values, **$3,4 \cdot 10^{-4}$ lb/ton**, will be the volatility and temperature-adjusted emission factor that will be used as **organic PM** fraction to define the general predictive equations.

In general, the emissions of MCEM PM and TOC (= THC + formaldehyde) are produced by the same asphalt dependent mechanism: both are the result of vaporization of organic material from the asphalt binder. However, the MCEM PM is less volatile and condenses into an aerosol, so would be different just the measuring method. Summing THC and MCEM PM from Plant D, the resulting value is not so far from the TOC and MCEM PM data from Plant C and considering the several adjustments, the difference is not so significant.

Therefore, for the purpose of developing emission factors for load-out operations, both the MCEM and TOC-THC data from the two plants were averaged, developing one representative equation.

4.2.3 Silo filling emissions from Plant C

The analysis and the volatility/temperature adjustments of the silo filling data were performed in the same way as described for the load-out data, but were collected just for the Plant C. However, in this case there was no background corrections to consider: it means that the adjustments were performed directly on the measured emissions.

In the following tables, the Temperature and Volatility-adjusted Particulate based and Volatile Organic Silo emissions data are collected.

	Run 1	Run 2	Run 3	Run 4	Average
Asphalt Loss on Heating (RIFOT, % by weight)	-0.362	-0.322	-0.284	-0.284	
Load out Temperature (°F)	321	316	291	291	
	lb/ton	lb/ton	lb/ton		lb/ton
Particulate Matter (PM) ^a	7.01e-04	5.83e-04	2.53e-04		5.12e-04
MCEM ^a	3.12e-04	3.06e-04	1.36e-04		2.51e-04
PAHs	lb/ton	lb/ton	lb/ton	lb/ton	lb/ton
Acenaphthene		8.37e-07	9.50e-07	1.76e-06	1.18e-06
Acenaphthylene		ND ^b	ND ^b	1.05e-07	3.49e-08
Anthracene		2.50e-07	3.14e-07	4.48e-07	3.37e-07
Benzo(a)anthracene		7.49e-08	1.46e-07	2.05e-07	1.42e-07
Benzo(b)fluoranthene		ND ^b	ND ^b	ND ^b	
Benzo(k)fluoranthene		ND ^b	ND ^b	ND ^b	
Benzo(g,h,i)perylene		ND ^b	ND ^b	ND ^b	
Benzo(a)pyrene		ND ^b	ND ^b	ND ^b	
Benzo(e)pyrene		ND ^b	ND ^b	7.14e-08	2.38e-08
Chrysene		2.83e-07	5.44e-07	7.61e-07	5.29e-07
Dibenz(a,h)anthracene		ND ^b	ND ^b	ND ^b	
Fluoranthene		2.43e-07	3.75e-07	4.75e-07	3.64e-07
Fluorene		2.64e-06	1.90e-06	3.05e-06	2.53e-06
Indeno(1,2,3-cd)pyrene		ND ^b	ND ^b	ND ^b	
2-Methylnaphthalene		1.23e-05	1.12e-05	1.62e-05	1.32e-05
Naphthalene		3.52e-06	4.02e-06	6.18e-06	4.57e-06
Perylene		9.25e-08	ND ^b	1.33e-07	7.52e-08
Phenanthrene		4.28e-06	3.58e-06	5.71e-06	4.53e-06
Pyrene		1.01e-06	9.50e-07	1.38e-06	1.12e-06

Table 22. *Temperature and Volatility adjusted Particulate based Silo emissions. (PLANT C)*

	Run 1	Run 2	Run 3	Average
Asphalt Loss on Heating (RTFOT, % by weight)	-0.362	-0.322	-0.284	
Load out Temperature (°F)	321	316	291	
	lb/ton	lb/ton	lb/ton	lb/ton
THC (ppm) ^a	8.03e-03	1.22e-02	1.62e-02	1.22e-02
Methane	9.24e-05	2.29e-06	ND ^b	3.16e-05
Acetone	2.14e-06	9.52e-06	8.53e-06	6.73e-06
CO	7.88e-04	2.68e-04	2.47e-03	1.18e-03
Ethylene	3.33e-05	4.01e-06	3.63e-04	1.33e-04
TOC ^c				1.22e-02
	lb/ton	lb/ton	lb/ton	lb/ton
Volatile HAP	lb/ton	lb/ton	lb/ton	lb/ton
Acrylonitrile	ND ^a	ND ^a	ND ^a	
Allyl chloride	ND ^a	ND ^a	ND ^a	
Benzene (M 0030)	3.83e-06	3.33e-06	4.44e-06	3.87e-06
Bromodichloromethane	ND ^a	ND ^a	ND ^a	
Bromoform	ND ^a	ND ^a	ND ^a	
Bromomethane	3.85e-07	1.05e-06	3.46e-07	5.95e-07
1,3-Butadiene	ND ^a	ND ^a	ND ^a	
2-Butanone	ND ^a	6.50e-06	7.80e-06	4.77e-06
Carbon Disulfide	ND ^a	4.38e-06	1.52e-06	1.97e-06
Carbon tetrachloride	ND ^a	ND ^a	ND ^a	
Chlorobenzene	ND ^a	ND ^a	ND ^a	
Chloroethane	ND ^a	1.44e-06	ND ^a	4.81e-07
Chloroform	ND ^a	ND ^a	ND ^a	
Chloromethane	1.36e-06	5.35e-06	1.61e-06	2.78e-06
Cumene (M 18)	ND ^a	ND ^a	ND ^a	
Dibromochloromethane	ND ^a	ND ^a	ND ^a	
1,2-Dibromoethane	ND ^a	ND ^a	ND ^a	
1,1-Dichloroethane	ND ^a	ND ^a	ND ^a	
	lb/ton	lb/ton	lb/ton	lb/ton
Volatile HAP	lb/ton	lb/ton	lb/ton	lb/ton
trans-1,3-Dichloropropene	ND ^a	ND ^a	ND ^a	
1,2-Epoxybutane	ND ^a	ND ^a	ND ^a	
Ethyl acrylate	ND ^a	ND ^a	ND ^a	
Ethylbenzene (M 0030)	4.86e-06	1.79e-06	7.22e-06	4.63e-06
Formaldehyde	1.97e-04	5.54e-05	ND ^a	8.41e-05
n-Hexane (M 0030)	1.71e-05	6.61e-06	1.33e-05	1.24e-05
2-Hexanone	ND ^a	ND ^a	ND ^a	
Iodomethane	ND ^a	ND ^a	ND ^a	
Isooctane	1.07e-07	4.65e-09	ND ^a	3.74e-08
Methyl methacrylate	ND ^a	ND ^a	ND ^a	
Methylene Chloride	7.59e-09	9.27e-08	ND ^a	3.34e-08
MTBE	ND ^a	ND ^a	ND ^a	
Styrene	3.79e-09	6.77e-07	1.31e-06	6.62e-07
1,1,2,2-Tetrachloroethane	ND ^a	ND ^a	ND ^a	
Tetrachloromethane	ND ^a	ND ^a	ND ^a	

Toluene (M 0030)	8.44e-06	3.84e-06	1.04e-05	7.56e-06
1,1,1-Tri chloroethane	ND ^a	ND ^a	ND ^a	
1,1,2-Tri chloroethane	ND ^a	ND ^a	ND ^a	
Trichloromethane	ND ^a	ND ^a	ND ^a	
Trichlorofluoromethane	ND ^a	ND ^a	ND ^a	
Vinyl acetate	ND ^a	ND ^a	ND ^a	
Vinyl bromide	ND ^a	ND ^a	ND ^a	
Vinyl chloride	ND ^a	ND ^a	ND ^a	
m-/p-Xylene (M 0030)	2.71e-05	9.79e-06	3.44e-05	2.38e-05
o-Xylene (M 0030)	7.89e-06	3.63e-06	9.42e-06	6.98e-06

Table 23. *Temperature and Volatility adjusted Volatile Organic Silo emissions. (PLANT C)*

[lb/ton]	Deposition of particulate
Particulate Matter PM	$7.26 \cdot 10^{-5}$
MCEM (PM organic)	$2.49 \cdot 10^{-6}$

Table 24. *Deposition of particulate during Silo filling operations in Plant C [30]*

Moreover, an increase in PM and MCEM values respectively of about $7.26 \cdot 10^{-5}$ lb/ton and $2.49 \cdot 10^{-6}$ lb/ton must be considered, connected with the reported deposition of particulate matter on the inside walls of the exhaust duct for silo filling operations (**Tab.24**). It means that the total temperature and volatility-adjusted values are:

- **Total PM** deposited (Tab.24) + sampled (Tab.22) = $7.26 \cdot 10^{-5} + 5.12 \cdot 10^{-4} = \mathbf{5.85 \cdot 10^{-4}}$ **lb/ton;**
- **MCEM** deposited (Tab.24) + sampled (Tab.22) = $2.49 \cdot 10^{-6} + 2.51 \cdot 10^{-4} = \mathbf{2.53 \cdot 10^{-4}}$ **lb/ton.**

As a consequence, the value related to the **inorganic PM** is given by the difference between these Total PM and MCEM, obtaining: $\mathbf{3.32 \cdot 10^{-4}}$ **lb/ton.**

4.3 Predictive Emission Factor Equations

The equations used to adjust the emissions data up to this moment to a common temperature and volatility are specific to the asphalt used during those tests. So, to arrive to a single equation that accounts for the different asphalts' physical properties, some additional adjustments are needed for the RTFOT data, since it was assumed that emissions are directly related to the loss-on-heating of the asphalt.

First, the *predicted loss-on-heating* at different temperatures for each asphalt was calculated through the plant-specific equations, **Equation 4** and **Equation 5**.

Then, these predicted values are corrected to a *loss-on-heating adjusted to -0,5 % RTFOT at 325°F*, using these equations:

$$V_{adj} = \frac{e^{((t+460)*0,0231-19,28)}}{e^{((325+460)*0,0231-19,28)}} * 0,5 \quad \text{Plant C] (10)}$$

$$V_{adj} = \frac{e^{((t+460)*0,0271-22,93)}}{e^{((325+460)*0,0271-22,93)}} * 0,5 \quad \text{Plant D] (11)}$$

V_{adj} = Loss-on-heating adjusted to a -0,5% RTFOT at 325°F;

T = Temperature in °F.

All these results, respectively related to Plant C (California) and Plant D (Massachusetts) are shown in Table 23:

Temperature (°F)	California Asphalt		Massachusetts Asphalt	
	Predicted RTFOT (%)	Adjusted to -0.5 % RTFOT @ 325 °F	Predicted RTFOT (%)	Adjusted to -0.5 % RTFOT @ 325 °F
270	-0.0893	-0.1404	-0.0456	-0.1122
275	-0.1002	-0.1575	-0.0522	-0.1285
280	-0.1125	-0.1768	-0.0598	-0.1472
285	-0.1262	-0.1985	-0.0686	-0.1686
290	-0.1417	-0.2228	-0.0785	-0.1931
295	-0.1590	-0.2501	-0.0900	-0.2212
300	-0.1785	-0.2807	-0.1031	-0.2535
305	-0.2004	-0.3150	-0.1181	-0.2903
310	-0.2249	-0.3536	-0.1352	-0.3326
315	-0.2524	-0.3969	-0.1549	-0.3810
320	-0.2833	-0.4455	-0.1775	-0.4365
325	-0.3180	-0.5000	-0.2033	-0.5000
330	-0.3570	-0.5613	-0.2329	-0.5728

Table 25. Predicted and adjusted Loss-on-heating values

After that, for each temperature, the average of the adjusted loss-on-heating values for asphalts from both plants was calculated. Then, a linear regression of the temperature and the natural logarithm of the adjusted loss-on-heating was performed to determine the equation constants. The results of this linear regression produce the following **Equation 12**:

$$\text{Loss-on-heating} = e^{((0.0251(T+460)) - 20.43)} \quad (12)$$

Equation. General relationship between Temperature and Loss-on-heating

This general Loss-on-heating equation, developed from the adjusted data related to asphalts used during testing in Plant C and D, was used to develop the Predictive Emission Factors Equations, concerning:

- Total PM;
- Organic PM (MCEM PM);
- TOC;
- CO.

So, using all the corrections shown up to this paragraph and using the volatility-temperature emission factors adjusted, it is possible to obtain [33]:

1) **Total PM** for drum-mix and batch mix plants, from Load-out operations:

$$\begin{aligned}
 \text{Total PM} &= 1.81 \text{ E-04} + 3.40\text{E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251)(T + 460) - 20.43)}}{e^{((0.0251)(325 + 460) - 20.43)}} \right] \\
 &= 1.81 \text{ E-04} + 3.40\text{E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251)(T + 460) - 20.43)}}{0.4836} \right] \\
 &= 1.81 \text{ E-04} + 1.41\text{E-03} (-V) e^{((0.0251)(T + 460) - 20.43)} \tag{13}
 \end{aligned}$$

Equation. Total PM emission factor for load-out operations.

where: **1.81 E-04** is the value that represents the *inorganic PM* emission factor from Plant C and was chosen because more reliable than the value in Plant D (Section 7.2.2);

3.40 E-04 represents the *organic PM* (MCEM) averaged from Plant C and D. Only this second value undergoes the general relationship between the loss-on-heating and temperature, because the organic emission is strictly related to these parameters.

With the same reasoning, it is possible to obtain the other predictive equations.

2) **Organic PM** for drum-mix and batch mix plants, from Load-out operations:

$$\begin{aligned}
 \text{Organic PM} &= 3.40 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 3.40 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 1.41 \text{ E-03} (-V) e^{((0.0251) (T + 460) - 20.43)} \tag{14}
 \end{aligned}$$

Equation. Organic PM emission factor for load-out operations.

3) **TOC** for drum-mix and batch mix plants, from Load-out operations:

$$\begin{aligned}
 \text{TOC} &= 4.15 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 4.15 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 1.72 \text{ E-02} (-V) e^{((0.0251) (T + 460) - 20.43)} \tag{15}
 \end{aligned}$$

Equation. TOC emission factor for load-out operations.

4) **CO** for drum-mix and batch mix plants, from Load-out operations:

$$\begin{aligned}
 \text{CO} &= 1.35 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 1.35 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 5.58 \text{ E-03} (-V) e^{((0.0251) (T + 460) - 20.43)}
 \end{aligned} \tag{16}$$

Equation. CO emission factor for load-out operations.

With the same method, it is possible to find the predictive equations also for *Silo Filling operations*:

1) **Total PM** for drum-mix and batch mix plants, from Silo filling:

$$\begin{aligned}
 \text{Total PM} &= 3.32 \text{ E-04} + 2.53 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 3.32 \text{ E-04} + 2.53 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 3.32 \text{ E-04} + 1.05 \text{ E-03} (-V) e^{((0.0251) (T + 460) - 20.43)}
 \end{aligned} \tag{17}$$

Equation. Total PM emission factor for Silo filling.

Since the resulting temperature and volatility adjusted PM and MCEM PM (organic fraction) emission factors for silo filling are respectively $5.85 \cdot 10^{-4}$ lb/ton and $2.53 \cdot 10^{-4}$ lb/ton, the inorganic PM that does not undergo the correction is the difference between these two values ($3.32 \cdot 10^{-4}$ lb/ton).

2) **Organic PM** for drum-mix and batch mix plants, from Silo filling:

$$\begin{aligned}
 \text{Organic PM} &= 2.53 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 2.53 \text{ E-04} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 1.05 \text{ E-03} (-V) e^{((0.0251) (T + 460) - 20.43)}
 \end{aligned} \tag{18}$$

Equation. Organic PM emission factor for Silo filling.

3) **TOC** for drum-mix and batch mix plants, from Silo filling:

$$\begin{aligned}
 \text{TOC} &= 1.22 \text{ E-02} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{e^{((0.0251) (325 + 460) - 20.43)}} \right] \\
 &= 1.22 \text{ E-02} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251) (T + 460) - 20.43)}}{0.4836} \right] \\
 &= 5.04 \text{ E-02} (-V) e^{((0.0251) (T + 460) - 20.43)}
 \end{aligned} \tag{19}$$

Equation. TOC emission factor for Silo filling.

4) CO for drum-mix and batch mix plants, from Silo filling:

$$\begin{aligned}
 \text{CO} &= 1.18 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251)(T + 460) - 20.43)}}{e^{((0.0251)(325 + 460) - 20.43)}} \right] \\
 &= 1.18 \text{ E-03} \left(\frac{V}{-0.5} \right) \left[\frac{e^{((0.0251)(T + 460) - 20.43)}}{0.4836} \right] \\
 &= 4.88 \text{ E-03} (-V) e^{((0.0251)(T + 460) - 20.43)} \tag{20}
 \end{aligned}$$

Equation. CO emission factor for Silo filling.

So, all these resulting general equations for *Drum mix* or *Batch mix* asphalt plants, respectively for Load-out and Silo Filling operations, are gathered in **Table 24**, as *Predictive Emission Factor Equations*. In the AP-42 *Compilation of Air Emissions Factors* of US EPA (*United States Environmental Protection Agency*), this table is reported to focus on the Hot Mix Asphalt Plant impact [4]:

Source	Pollutant	Equation
Drum mix or batch mix plant load-out (SCC 3-05-002-14)	Total PM ^b	EF = 0.000181 + 0.00141(-V)e ^{((0.0251)(T+460) - 20.43)}
	Organic PM ^c	EF = 0.00141(-V)e ^{((0.0251)(T+460) - 20.43)}
	TOC ^d	EF = 0.0172(-V)e ^{((0.0251)(T+460) - 20.43)}
	CO	EF = 0.00558(-V)e ^{((0.0251)(T+460) - 20.43)}
Silo filling (SCC 3-05-002-13)	Total PM ^b	EF = 0.000332 + 0.00105(-V)e ^{((0.0251)(T+460) - 20.43)}
	Organic PM ^c	EF = 0.00105(-V)e ^{((0.0251)(T+460) - 20.43)}
	TOC ^d	EF = 0.0504(-V)e ^{((0.0251)(T+460) - 20.43)}
	CO	EF = 0.00488(-V)e ^{((0.0251)(T+460) - 20.43)}

Table 26. Predictive Emission Factor Equations [lb/ton] (Rating C) – [4]

So, the inputs necessary to use these general equations are the asphalt volatility and the mixing temperature related to the technology involved, obtaining the emission value for a certain pollutant expressed in lb/ton.

As mentioned in the theoretical explanation of the topics with the two case studies, in terms of reliability, at the data concerning Plants C and D were assigned an A Rating; however, the rating related to the final *Predictive Emission Factors Equations* is C. This change is connected with the fact that blending together the results coming from different plants, applying averages, making corrections and so on, unavoidably leads to an uncertainties growth. However, a C Rating represents a very good target achieved for this kind of issues.

4.4 Estimation of WMA-HMA impact in terms of Load-out and Silo filling emissions

In this paragraph, the Predictive Emission Factor Equations gathered in **Table 24** will be applied to the data (WMA and HMA average production temperatures) found in NCHRP Project 9-47A [25] treated in Chapter 3. In this way, the Load-out and Silo filling emissions to compare WMA and HMA technology will be estimated, observing accurately the production temperature effect.

Site	Plant ¹	Mix	Avg. Stock-pile Moist. (%)	Avg. Prod. Rate (TPH)	Avg. Mix Temp. (°F)
Washington	Uninsulated PF drum	HMA	2.6%	316	325
		Maxam foam	3.0%	310	285
Virginia	Double barrel	HMA	2.3%	270	318
		Astec foam	2.1%	221	288
Michigan	Uninsulated PF drum	HMA	3.6%	310	300
		Advera	3.9%	323	269
		Evotherm 3G	4.1%	320	269
Montana	Partially insulated PF drum	HMA	1.3%	370	298
		Evotherm DAT	1.5%	378	252
Indiana	Insulated CF dryer	HMA	3.2%	292	300
		Gencor foam	3.5%	300	277
		Evotherm 3G	3.8%	300	256
		Heritage wax	3.8%	279	268
New York	Batch-mini drum uninsulated dryer	HMA	3.1%	271	332
		Cecabase RT	3.4%	244	240
		SonneWarmix	2.4%	267	252
		BituTech PER	3.6%	268	253

Table 27. Mixing temperatures for HMA and WMA - Project 9-47A [25]

In **Table 25**, it is possible to observe 6 different sites and the variability of asphalt mixture (HMA and WMA) tested for each site. In the last column, the Average Mixing Temperature applied for each mixture is reported. In general, considering all these projects, it has been recorded an average temperature difference, between Hot and Warm technology, of about 48°F (27°C). Specifically:

- Average **HMA** mixing temperature: **315°F (157°C)**;

- Average **WMA** mixing temperature: **267°F** (130°C);

The asphalt volatility value has to be, in general, in a range of -0,5 to 0,5 %: so, for this example it may be used the standard default value **V = -0,5 %**.

In **Table 26** are collected the final results obtained applying the predictive equations, changing the unit of measure from lb/ton to g/ton.

	Load-out Emission Factors			Silo filling Emission Factors		
g/ton	WMA	HMA	% Reduction	WMA	HMA	% Reduction
Total PM	0.12	0.20	40 %	0.18	0.24	25 %
Organic PM	0.036	0.12	70 %	0.026	0.086	69.71 %
TOC	0.44	1.47	70.12 %	1.30	4.33	69.93 %
CO	0.14	0.48	71.10 %	0.13	0.42	68.87 %

Table 28. Load-out and Silo filling emissions impact-HMA vs WMA [g/ton]

It is interesting to observe the results obtained with these calculations: there is a clear average reduction by 70 % for each compound using the warm technology instead of the hot one. The only exception is represented by the total PM, characterized by a reduction of 40 % in load-out emissions and 25 % in silo filling ones. It can be linked to the fact that the total PM is mainly inorganic and it is not so affected by temperature changes.

So, even in these plant operations it has been possible to define the environmental benefit of using the Warm mix asphalt to replace the conventional Hot mix asphalt technology.

5- Observations about transportation phase and road paving impact

5.1 Asphalt mixture transportation phase from the production plant to the worksite

In this work thesis, the transportation step is considered to be negligible compared to the emissive impact of plant operations, on the basis of what is found in the literature [27]. Nevertheless, one of the advantages in using WMA is that it is possible to transport this mixture at higher distances from the plant than in case of HMA: it means that there may be a higher impact concerning the CO₂ emissions related to trucks. So, the question should be: *does this impact risk losing the benefits of WMA in terms of CO₂ production in plant?*

For instance, it should be considered a truck average capacity of 30 tons of asphalt transported and an average full-truck fuel consumption of about 2.4 – 2.9 km/l. While, diesel oil, in terms of energy conversion, corresponds to 38MJ/l and it is characterized by a CO₂ emission factor of 74,100 mg/MJ [28].

On this basis, 2 different scenarios must be assumed, involving respectively HMA and WMA, supposing a higher transportation distance for the WMA and an average value of CO₂ produced at the plant related to the previous studies:

- **HMA:** transportation of 30 ton of asphalt concrete at a distance of 30 km, corresponding to about 11 l of diesel fuel (2.4 – 2.9 km/l). Consider a typical CO₂ production of 18 kg/ton of mixture at the plant, presented in literature [29], dealing with the use of natural gas;
- **WMA:** transportation of 30 ton of asphalt concrete at a distance of 50 km, corresponding to about 18 l of diesel fuel (2.4 – 2.9 km/l). Consider a typical CO₂

production of 12 kg/ton of mixture at the plant [29] dealing with the use of natural gas.

Dealing with the first Scenario (HMA), firstly, it will be calculated the kg of CO₂ produced during the truck transportation, linked to the diesel fuel consumption, and then, the kg of CO₂ connected with the production of 30 ton of asphalt at the plant. The same calculation will be done for the second Scenario (WMA).

$$1] \quad 11 \text{ l} * 38 \text{ MJ/l} * 74100 \text{ mgCO}_2/\text{MJ} = \mathbf{31 \text{ kg CO}_2}$$
 produced during HMA truck transportation.

$$30 \text{ ton} * 18 \text{ kgCO}_2/\text{ton} = \mathbf{540 \text{ kg CO}_2}$$
 emitted to produce 30 ton of HMA at the plant.

$$2] \quad 18 \text{ l} * 38 \text{ MJ/l} * 74100 \text{ mgCO}_2/\text{MJ} = \mathbf{50.68 \text{ kg CO}_2}$$
 produced during WMA truck transportation.

$$30 \text{ ton} * 12 \text{ kgCO}_2/\text{ton} = \mathbf{360 \text{ kg CO}_2}$$
 emitted to produce 30 ton of WMA at the plant.

These calculations are significant to obtain a rough CO₂ balance on 30 ton of asphalt mixture produced and transported, considering in case of WMA a lower CO₂ emission at the production plant but a higher transportation emission, connected to the potential longer distance allowable.

Indeed, these results say that using WMA it will be emitted 180 kgCO₂ less than with the HMA at the production plant (for 30 ton of mixture); on the other hand, it will be produced 20 kgCO₂ more than in the HMA scenario in the transportation phase, linked to the added fuel impact related to the longer distance with the truck.

To sum up, within these boundary conditions, it means that involving the Warm Mix technology can be assured anyway a 28,02% of reduction in CO₂ impact.

5.2 Road paving phase

In this work-thesis, the impacts related to asphalt plant operations have been accurately analysed; however, it's important also to observe what happens during the last step: laying down phase, with the spreading of the asphalt mixture at the paving site. Indeed, it is considered a sensitive phase because of the workers exposure, as well as for the relatively significant environmental impact.

The laying down is not considered a well-defined “in-point” source from which emissions are channelled into the atmosphere (e.g. industrial gas stacks): it is a “non-point” source of diffuse or fugitive emissions.

In this chapter, the road paving effect of Hot mix asphalt will be compared with that of the Warm mix one, as far as possible.

In general, data in literature and more recent studies reveal that the paving of WMA results in a significant reduction of asphalt fumes at the paving site, and usually this reduction is also clearly visible during placement (Figure 15) [34].



Figure 14. Visible asphalt fumes at the asphalt paver (HMA vs WMA) [34].

The problem is that in the case of these non-channelled emissions, the measuring methods were influenced by non-homogeneous dispersion of gases and particles in the atmosphere: so, the collected data are only indicative of these concentrations. The other hindrance is linked to the amount generally detected: it is very small, especially for the VOC and PAH, or even non-existent for certain compounds [35].

In some case studies, the doubts about WMA benefits were connected to the use of chemical additives of unknown composition, which could be released during road paving operations resulting in hazard for the road workers, and to the use of a higher RAP% [36]. Indeed, RAP in the past was usually heavily contaminated with tar, known to contain large amounts of toxic Polycyclic Aromatic Hydrocarbons PAH. However, nowadays, especially in Italy, the RAP does not contain tar anymore: so, as mentioned by the Ministerial Decree DM 69/2018, it is not classified as a potentially hazardous waste.

It has been demonstrated that at typical paving temperatures (140-160°C), field PAH quantity is very low and often approaches the level of detection for common methods. The amount and composition of PAH were markedly influenced by changes in temperature, and binder temperature below 190°C were not high enough to initiate significant PAH formation [37], [38].

In general, few emission measurements during road construction were conducted so far, due to the complex sampling and analytical technique. Thus, the results were not so representative, because of the short test fields, sampling times, small sample gas volumes and relatively small amounts of emissions in this step [36]. Moreover, direct comparisons to different case studies are difficult because of various sampling and testing protocols used in different countries [7]. It means that more in-depth research needs to be carried out on road paving operations emissions [35]: indeed, the literature consulted shows that so far these emissions have not been empirically quantified or collected in a database and consequently, for this part of this thesis, it is not possible to derive some predictive equations to estimate and compare the impact of WMA and HMA.

For these reasons, in the following two Sections, two different case studies will be analysed just to obtain as detailed as possible information about the potential different impact between WMA and HMA even during laying-down phase.

5.2.2 “New York and Indiana” case study

It is known that asphalt is the non-distillable fraction of crude oil, it means that small amounts of volatile and semi-volatile organic compounds are trapped in this viscous material: for this reason, the release of these emissions constitute the potential risk for worker exposure.

In October 2011, the International Agency for Research on Cancer stated that “occupational exposures to straight-run bitumens and their emissions during road paving are *possibly carcinogenic* to humans” [51]. So, a lot of studies emphasize the need for reducing worker exposure to asphalt emissions. The *National Institute for Occupational Safety and Health* (NIOSH) recommended the use of good work practices, including reduction of the asphalt mix temperature.

For this reason, the use of Warm Mix Asphalt may result a good solution in order to reduce this emissions impact: few peer reviewed publications specifically document this promoted benefit of WMA. For example, D’Angelo et al., (2008) [7] indicated 30-50 % reductions in asphalt fumes and PAH, compared to the conventional HMA.

In Chapter 3, it has already been used the NCHRP Project 9-47A to deal with energy savings connected with the fuel combustion process in the dryer: within this project, the Indiana and New York sites were also used to collect data on the breathing zone exposure to asphalt fumes for the paving crews [25]. This study was designed to compare WMA versus HMA applications under similar conditions, controlling many variables in the field. Specifically, 3 different WMA technologies were compared to one HMA at each of the two sites mentioned before. Specifically, the research approach is based on 8 workers (one crew in Indiana and one in NY) monitored for four consecutive days (1 with HMA and 3 using different WMA tech) and meteorological data were recorded (air temperatures, wind speed,

humidity). Within a given site, controlled variables included asphalt source, aggregate, RAP%, plant, paving equipment and crew.

Each worker wore 2 sorbent tube samplers: the breathing zone air entered a membrane filter first, followed by the sorbent tube (Figure 16), allowing the determination of *Total Particulates (TP)*, *Benzene Soluble Fraction (BSF)* and *Total Organic Matter (TOM)*.



Figure 15. Sorbent tube samplers wore by a worker in Indiana site [25].

The BSF is usually considered as a key parameter for studying this kind of exposure emissions. However, collecting these measurements for 3 different WMA technologies, it has been observed that the Benzene Soluble Fraction levels were all below the detection level (*bdl*).

Since all samples contained detectable levels of Total Organic Matter TOM, this was selected as the primary tool for evaluating differences in exposure between HMA and WMA. In general, TOM included hydrocarbons ranging from C6 to C42 (carbon atoms number). In Table 27, the average temperatures for each mixture used in both the sites are collected.

	Mix Temperature behind Screed, °C	Difference, °C
Hot Mix Asphalt, Indiana	126	IN Reference
Gencor Foam	114	12
Evotherm 3G	111	15
Heritage Wax	116	10
Hot Mix Asphalt, New York	161	NY Reference
Cecabase RT	106	55
SonneWarmix	109	52
BituTech PER	117	44

Table 29. Average Temperature of the Asphalt concrete behind the screed [25]

It is interesting to see that the Indiana HMA has a temperature of 126°C, so in the common range concerning WMA (100-140°C); so, the difference compared to the other 3 WMA mixture is only 15°C or less. While, dealing with the New York site, the temperature of the HMA is about 160°C and, compared to the warm mixtures, the difference is higher, with an average of 50°C.

Both sites used PG 64-22 asphalt for HMA and WMA, but the source of asphalt is different and even the paver machines are very different.

TOM results are listed in **Table 28** for the Indiana site, in **Table 29** for the New York site, with a statistics summary shown in **Table 30**.

Product	Date	Tonnage	Lab ID	Description	Minutes ¹	L air ²	TOM (mg/m ³)	Experiment Average TOM (mg/m ³)
Hot-Mix, IN	9/14/2010	1200	51	Operator	350	721	0.30	0.32
			52	Operator	285	581	0.17	
			53	Raker	429	875	0.25	
			54	Raker	430	854	0.24	
			55	Screedman	430	851	0.52	
			56	Screedman	430	858	0.53	
			57	Foreman	430	894	0.21	
			58	Foreman	430	882	0.33	
Gencor Foam	9/15/2010	1187	61	Operator	425	871	0.05	0.12
			62	Operator	425	876	0.05	
			63	Screedman	424	837	0.13	
			64	Screedman	424	854	0.09	
			65	Raker	419	848	0.12	
			66	Raker	422	850	0.11	
			67	Foreman	432	886	0.19	
			68	Foreman	432	873	0.25	
Evothem 3G	9/16/2010	881	71	Operator	262	542	0.27	0.34
			72	Operator	262	542	0.30	
			73	Screedman	268	531	0.45	
			74	Screedman	268	547	0.58	
			75	Raker	267	545	0.27	
			76	Raker	267	542	0.31	
			77	Foreman	264	546	0.29	
			78	Foreman	264	539	0.30	
Heritage Wax	9/16/2010	890	81	Operator	225	464	0.04	0.15
			82	Operator	225	467	0.05	
			83	Screedman	227	452	0.24	
			84	Screedman	227	462	0.30	
			85	Raker	228	463	0.12	
			86	Raker	228	462	0.12	
			87	Foreman	230	475	0.12	
			88	Foreman	230	470	0.18	

Table 30. *Indiana* site information and TOM data for all the samples [25].

Product	Date	Tonnage	Lab ID	Description	Minutes ¹	L air ²	TOM (mg/m ³)	Experiment Average TOM (mg/m ³)
Hot Mix, NY	10/20/2010	1100	49	Operator	430	837	2.78	2.21
			50	Operator	430	834	2.97	
			51	Screedman	436	859	2.15	
			52	Screedman	436	857	1.62	
			53	Raker	447	871	1.84	
			54	Raker	447	896	1.91	
			55	Laborer	434	862	2.21	
			56	Laborer	434	860	2.20	
Cecabase RT	10/19/2010	800	41	Operator	377	744	1.46	1.17
			40	Operator	377	752	1.78	
			42	Screedman	370	738	1.02	
			38	Screedman	370	733	1.31	
			44	Raker	373	724	1.11	
			43	Raker	376	759	1.25	
			39	Laborer	387	777	0.58	
			37	Laborer	387	778	0.87	
SonneWarmix	10/21/2010	780	61	Operator	345	695	1.79	1.40
			62	Operator	345	667	1.57	
			63	Screedman	352	683	1.37	
			64	Screedman	352	681	1.46	
			65	Raker	362	723	1.29	
			66	Raker	362	721	0.78	
			67	Laborer	385	765	1.41	
			68	Laborer	385	759	1.51	
BituTech PER	10/22/2010	798	73	Operator	346	696	2.14	1.48
			74	Operator	347	700	1.81	
			75	Screedman	382	764	1.60	
			76	Screedman	382	745	1.58	
			77	Raker	342	691	1.77	
			78	Raker	343	680	1.73	
			79	Laborer	388	770	1.48	
			80	Laborer	387	766	1.33	

Table 31. New York site Information and TOM data for all the samples [25].

The column “Description” refers to the different workers positions during asphalt paving operations, to define the possible variations in exposure. Moreover, all the information about tonnage, the time sample collector running and the litres of air collected by the sampler are gathered.

Dealing with the average TOM concentrations, **Table 30** is perfect to put in comparison HMA to WMA effects, considering a statistical standpoint with minimum, maximum and average values, together with standard deviation and the total number of samples analysed.

mg/m ³	WMA, NY	HMA, NY	WMA, IN	HMA, IN
Average	1.42	2.21	0.21	0.32
Minimum	0.58	1.62	0.04	0.17
Maximum	2.14	2.97	0.58	0.53
Standard Deviation	0.36	0.46	0.13	0.14
Number	24	8	24	8

Table 32. Summary of TOM data collected in the two sites [25].

It can be easily observed that TOM concentrations for the New York site are about seven times higher than those for Indiana site, probably because the source of the asphalt was different (different asphalt volatility), as well as the difference in temperature between HMA and WMA is really higher in NY [25]. In both the cases, looking at the average values in **Table 30**, it resulted in about 33 % reduction in TOM exposure going from HMA to WMA. Obviously, thanks to the clear difference in temperature between the hot and warm technology, the New York data showed a statistically more significant analyses than Indiana ones. So, TOM demonstrates to be a useful measure for assessing reductions in worker breathing zone exposure to assess the use of WMA as an alternative to HMA.

For what concerns the analysis of Polycyclic Aromatic Hydrocarbons PAH in these sites, 22 of the 40 individual PAHs tested were below the detection limit (bdl) for the eight samples tested. However, it has been observed that not all the asphalts are the same: here the source resulted in significantly different breathing zone exposure levels.

5.2.3 “Colorado and Mississippi” case study

During placement, the paver’s auger (screed) area is the greatest source of emissions [16]; while, not all studies agree on the specific health effects, there is strong enough evidence to show that such effects can be present [26].

Field monitoring of asphalt emissions was conducted by the U.S. Army Engineer Research and Development Centre (ERDC) to collect quantitative data to determine the potential reduction in fumes associated with the use of WMA [26].

The two sites selected for this project are presented in the following table, located respectively in Colorado and Mississippi:

Test Site	Location	Test Section Description	Date Monitored	Average Placement Temperature (°F)
1	Eagle, Colorado	20% RAP HMA	May 16, 2013	138
		20% RAP WMA	May 17, 2013	126
2	Okolona, Mississippi	15% RAP WMA	Jun 26, 2013	132
		15% RAP HMA	June 27, 2013	139

Table 33. Test site information [26].

In Colorado, the binder grade used is PG 64-28, while in Mississippi is PG 67-22; it changes also the RAP % involved. Both the plants used foaming to produce WMA.

It must be considered that also in this case, such as for Indiana in Section 7.1, the placement temperature difference between WMA and HMA is very low: $\Delta T = 12^{\circ}\text{C}$ in Test Site 1; $\Delta T = 7^{\circ}\text{C}$ in Test Site 2.

At each test site, 5 workers were monitored during the placement operations (Figure 17) of each mix using air sampling pumps operating at a flow rate of $2,0 \pm 0,2$ L/min.



Figure 16. Typical sampler configuration on worker [26].

Measurements of Total Particulates (TP) and Benzene Soluble Fraction (BSF) was used to analyse the filter portion of the sampling train. TP in general refers to the nonspecific gravimetric amount of organic and inorganic particles and represents the total dust collected on the filter of the sample. The BSF is the gravimetric amount of TP that is soluble in

benzene: it is theoretically 100% of the organic fraction of the TP including also aliphatic and aromatic compounds.

Furthermore, gas chromatography with flame ionization detection (GC/FID) was used to analyse the sorption tube portion of the sampling train, in order to quantify the Total Organic Matter (TOM), providing the amount and composition of the fumes.

In **Figure 18** and **19**, the TP values for test site 1 and test site 2 are presented, respectively. In general, in Colorado the particulate concentrations seems to be higher during WMA placement than during the HMA one. While, in Mississippi, exactly the opposite was observed. However, it is interesting to observe that TP is mainly the dust collected on the filter, so it is not expected to correlate so much with asphalt-placement temperature changes. In Colorado (**Fig.18**), the range of individual exposure to TP is 0,17-0,85 mg/m³ (average 0,36 mg/m³); the screedmen resulted to have the highest exposure to TP. In Mississippi (**Fig.19**) the range is larger: 0,12-2,26 mg/m³ (average 0,71 mg/m³); the highest exposure in this case is suffered by the MTV operator during HMA placement.

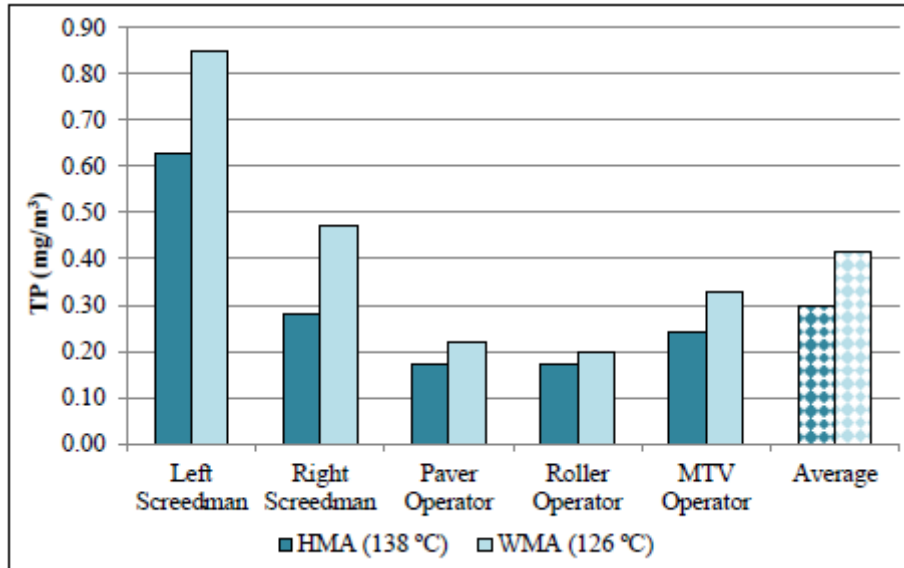


Figure 17. Worker exposure to TP in Colorado (Test site 1) [26]

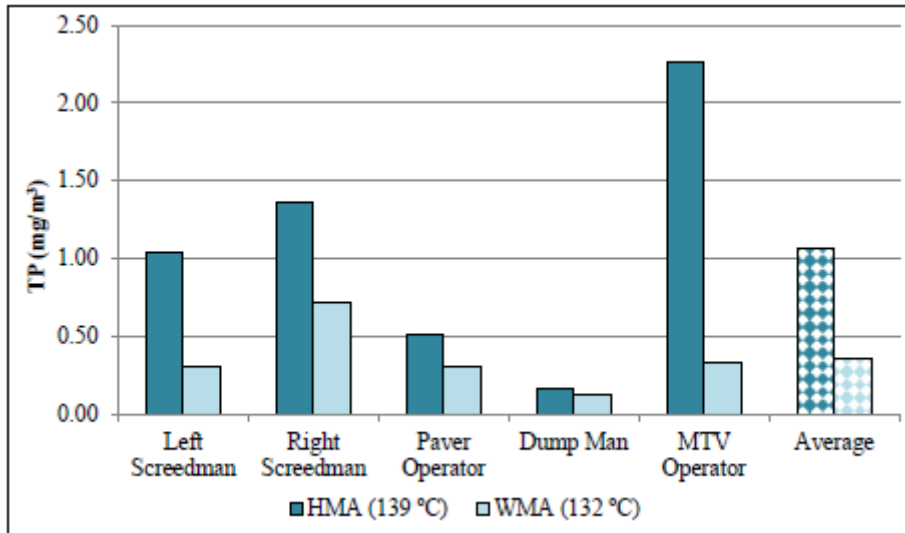


Figure 18. Worker exposure to *TP* in Mississippi (Test site 2) [26]

Then, in **Figure 20** and **21**, the BSF values for Test Site 1 and 2 are listed, respectively.

On average (last values of each graph), in Colorado (**Fig.20**) the same impact comparing HMA to WMA placement emissions can be observed; the range of exposure is 0,01-0,08 mg/m³ (average 0,036 mg/m³) and even in this case, the workers with the highest exposure were the screedmen (in HMA placement) and the roller operators (in WMA placement). In Mississippi (Test Site 2), the BSF concentrations are clearly lower during WMA placement than HMA one. The range of exposure is 0,04-0,23 mg/m³ (average 0,11 mg/m³) with the highest exposure to BSF for the screedmen.

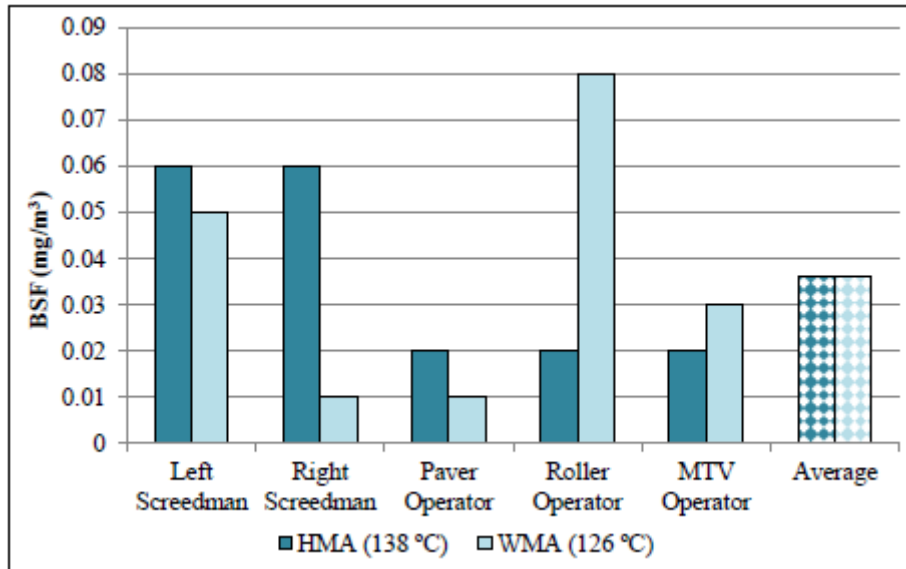


Figure 19. Worker exposure to *BSF* in Colorado (Test Site 1) [26]

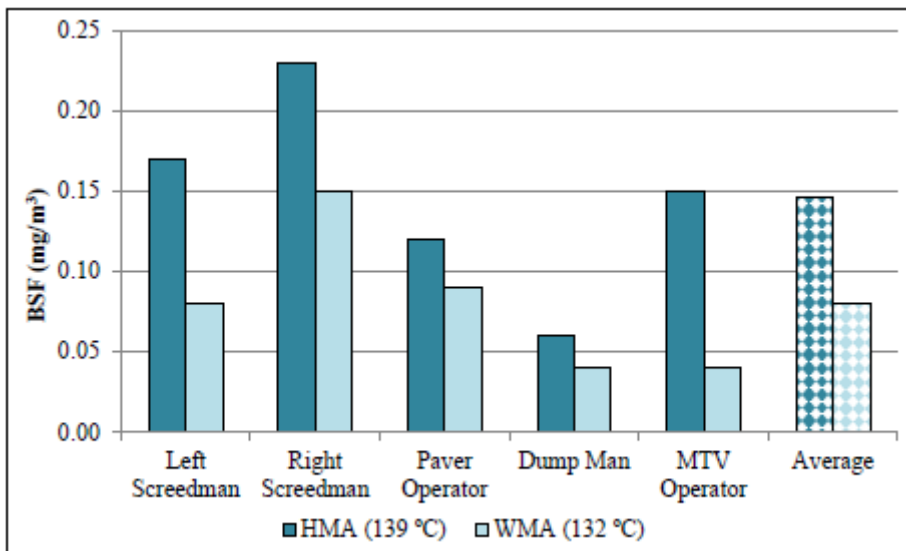


Figure 20. Worker exposure to *BSF* in Mississippi (Test Site 2) [26]

Dealing with the Total Organic Matter, the results from GC/FID are compared in **Figure 22** and **23**, respectively for Site 1 and 2. In Colorado, TOM concentrations were higher during HMA placement; the range of individual exposure to TOM is 0,05-0,45 mg/m³ (average 0,20 mg/m³). The left screedman and the MTV operator have the highest concentrations of TOM. At Test Site 2, TOM concentrations were similar for both HMA and WMA, remembering that at this site the placement temperature were similar for the two technologies. The individual exposure range is 0,15-3,35 mg/m³ (average 1,29 mg/m³), with the right screedman who had the highest exposure to TOM.

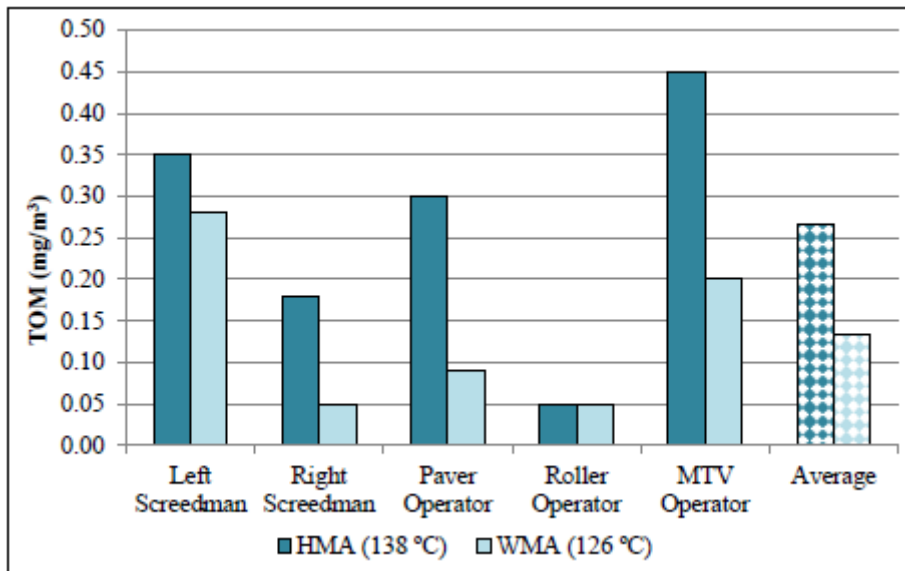


Figure 21. Worker exposure to *TOM* in Colorado (Test Site 1) [26]

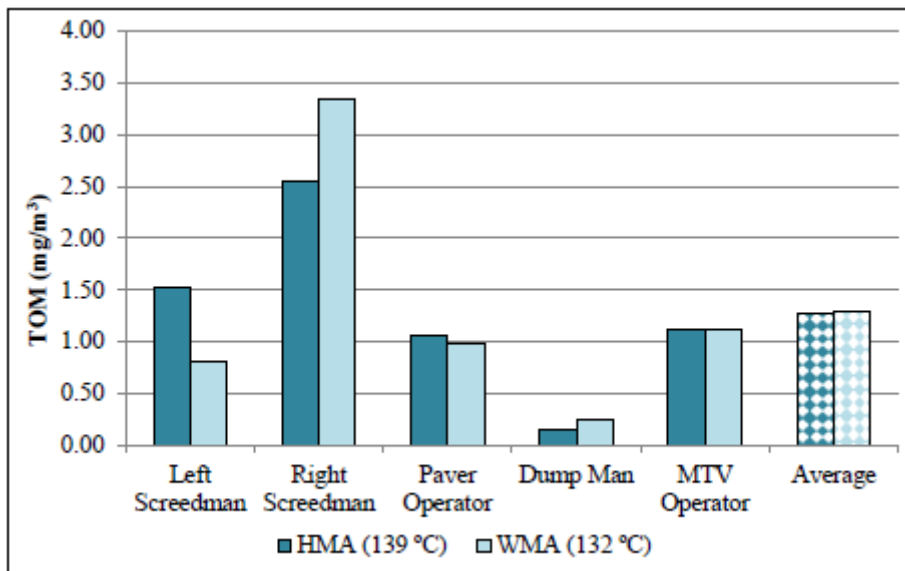


Figure 22. Worker exposure to *TOM* in Mississippi (Test Site 2) [26]

So, in general, at **Test Site 1**, TOM emissions were reduced by 50% using WMA instead of HMA, while the average BSF remains the same; the only exception is for TP, where no correlations were expected with application temperature. On the other hand, at **Test Site 2**, all emissions were reduced with the use of WMA, except TOM that increase by only 1,7 %. This slight increase could also have been influenced by test variability and the placement

temperatures in Mississippi were not so different. Regarding the TP, there is a reduction by 67%; while, BSF is reduced by 47%.

However, this kind of mixed results are typical in field observations that depend on different variables that cannot be controlled at the same time: weather, sampling process, paving crew, equipment, construction logistics and landscape, among others. Specifically, it is important to focus on the different impact related to a different worker position.

Some sampling techniques for analysing workers exposure are not appropriate for this purpose because the results are often below the detection limits.

So, all these factors complicate the process of quantifying potential reductions associated with the use of Warm Mix Asphalt compared to the conventional Hot Mix one.

For this reason, nowadays we are not able to estimate correctly and reliably this kind of placement emissions using some predictive equations, but through these empirical observations it is possible to observe a quite common and approximate trend of emissions reduction applying warm technology.

6- Impact of WMA in an Italian case study

Dealing with the road paving sector, Italy is the European Nation with the highest number of companies working in this field, not less than 3500 – 4000. Even the number of Asphalt production plant is really high: more than 800 plants are present in our regions, with 693 of these perfectly functioning.

In **Table 32**, the asphalt plants spread across Italian regions, with their average hourly production [ton/hr] and the type of plant, are listed.

Regione	N° Impianti	Funzionanti	Produzione oraria / Tipo Impianto						
			< 80	80+120	120+170	160+200	200+250	>250	Continui
Valle d'Aosta	9	8	1	5	2				
Piemonte	80	70	6	18	23	15			8
Liguria	35	30	8	14	6				2
Lombardia	105	95	4	19	21	18	10	5	13
Trentino Alto Adige	28	25	2	4	10	6	3		
Veneto	55	50	4	9	10	10	11	2	4
Friuli Venezia G.	20	18	4	6	3	2	2		1
Emilia Romagna	52	50	2	6	18	6	9	2	7
Toscana	56	46	2	16	13	5	4		6
Marche	29	24	4	11	5	3	1		
Umbria	25	21	1	8	6	2	1		3
Abruzzo	35	29	5	12	8	2			2
Lazio	75	61	3	19	15	8	2		14
Molise	6	6		2	2	1			1
Puglia	53	47	6	12	14	4	2	1	8
Campania	39	35	7	6	10	4	2	1	5
Basilicata	19	15	3	5	6				1
Calabria	25	20		3	6	4	2		5
Sicilia	36	32	5	10	9	2			6
Sardegna	20	16	2	7	4	2			1
Totale	802	693	69	192	191	94	49	11	87

Table 34. Italian distribution of asphalt plants, on regional basis [39].

In Italy, the road network amounts to about 480000 km and to maintain the efficiency of these roads in their lifetime, not less than 40 million of asphalt tons are needed every year [39].

It means that the environmental impact of the asphalt concrete production must be considered, controlling the energy consumption, the machine/equipment efficiency, using emission control countermeasures and less impacting technology (i.e. WMA).

6.1 Stack emissions evaluation

In this chapter, the whole analyses presented in this work-thesis is replayed for an Italian real case study, in which partially the stack emissions data have been directly measured, excluding GHGs.

This comparative test is dealing with the production of 3 different WMA technologies (mixing temperature 130°C) and one HMA assumed as reference (mixing temperature 170°C).

The emissions control connected to the production temperatures of the four asphalt mixtures has been carried out through direct measurement of gaseous and particulate emissions from the dryer: Particulate Matter, CO, NO_x, SO_x, VOC, PAH. Specifically, all the data have been collected under the same boundary conditions (humidity, ambient temperature, wind direction and intensity, plant structure).

- 1st Sampling: HMA, with RAP = 25%, modified hard bitumen;
- 2nd Sampling: WMA **WC3**, with RAP = 30%, modified hard bitumen and a chemical additive named C3;
- 3rd Sampling: WMA **WC2**, with RAP = 25%, modified hard bitumen and a chemical additive named C2;
- 4th Sampling: WMA **WC1**, with RAP = 25%, modified hard bitumen and a chemical additive named C1.

In **Table 33** all the direct measurement results about these asphalt mixtures are listed, expressed in mg/Nm³. In the last column, the average WMA stack emissions are subtracted to the HMA ones, obtaining the difference in emission **Δmg/ton**.

Emissions [mg/Nmc]	HMA	WC3	WC2	WC1	WMA average	Δ mg/ton emission
NOx	61.8	47.4	52.4	57.4	52.4	9.4
VOC	10.4	6.7	8.09	10.5	8.43	1.97
CO	1021	1228	1210	1081	1173	-152
Particulate	11.8	9.58	12.3	12.6	11.5	0.3
SOx	129	128	168	83.5	126.5	2.5

Table 35. Stack emissions measured for all the asphalt mixtures produced at the Italian asphalt plant.

In the Annexes of the D. Lgs. 152/2006 known as “Testo Unico Ambientale” (Italian Legislation on emissions), the limits concerning conveyed emissions from different production processes in plants are established. Specifically, dealing with plants for the production of asphalt mixture, involving road construction products and considering an oxygen content of 17% in the gaseous effluent from the chimney, the Emission Limit Values - ELV are collected in **Table 34**.

Chemical Parameters	Emission Limit Value – ELV [mg/Nm ³]
NOx	500
VOC	-
CO	-
Particulate	20
Sox	1700
PAH	0,1

Table 36. Emission Limit Values (D. Lgs 152/2006) concerning stack emissions in Asphalt plant

First of all, it should be emphasized that all the concentration values measured at the plant (Table 34) are below the Emission Limit Values (ELV) imposed by the Italian legislation (Table 35). Furthermore, a threshold for volatile organic compound (VOC) and for carbon monoxide (CO) is not present. Even if they are not considered in the D. Lgs, the *SITEB-Strade Italiane E Bitumi*, which is an association composed by groups of the foremost

operators regarding the road and bitumen sector, set out some reference values on the basis of several direct measurement in functioning plants: CO = 500 mg/Nm³; VOC = 150 mg/Nm³ [40].

To analyse the impact of these emissions (**Table 34**) in an easier way and connect them directly with the production activity, it can be useful to transform the unit of measure regarding the emissive data into g of pollutant per ton of asphalt produced [g/ton]. To obtain this kind of result, the *normalized air flowrate* [Nm³/h] in terms of average value of air flow considered during the measurement period, and the *operational potential* [ton/h] of the plant exactly during the measurement for each mixture must be known. These data are summarized in **Table 35**.

Asphalt mixture	HMA	WC3	WC2	WC1
Normalized Air Flowrate [Nm ³ /h]	41,208	41,799	39,920	41,914
Max Operational Potential [ton/h]	180	180	180	180
Load during measurement [%]	83 %	83 %	92 %	83 %
Operational Potential during measurement [ton/h]	150	150	165	150

Table 37. Asphalt plant parameters during dryer emissions measurement.

So, each emission concentration value listed in **Table 33** must be multiplied by the corresponding normalized air flowrate and then divided by the operational potential during measurement, obtaining the mg/ton related to each pollutant. Dividing again by 1000 it will be found g/ton, as shown in **Table 36**.

Example of calculation:

CO for the HMA mixture, considering a Normalized Air Flowrate of 41,208 Nm³/h and an Operational potential during measurements equal to 150 ton/h:

$$\text{CO} = [(1,021 \text{ mg/Nm}^3 * 41,208 \text{ Nm}^3/\text{h}) / 150 \text{ ton/h}] / 1,000 = 280.51 \text{ g/ton}$$

Emission [g/ton]	HMA	WMA average	Δ g/ton emission	Δ %
Particulate	3.25	3.02	0.23	7 %
CO	280.51	312.23	-31.72	-11 %
NOx	17	13.96	3.04	18 %
SOx	35.44	33.18	2.26	6.5 %
VOC	2.86	2.24	0.62	22 %

Table 38. Stack emissions expressed in g/ton.

As mentioned before, the three warm mixtures have been produced with a mixing temperature of 130°C, it means with a reduction of 40°C compared to the reference HMA. From **Table 36**, considering the *WMA average* for the comparison to the *HMA*, it can be observed the difference in amount of emission Δ g/ton or in percentage Δ % from direct measurement of the stack emissions:

- **NO_x**: Using a warmer technology, the benefit in terms of nitrogen oxides production is clear. It results in a reduction of about 18% related to the decrease in production temperature;
- **VOC**: Concerning the organic matter, it can be observed a similar trend of reduction, close to the 22% using WMA. In general, the VOC emissions of all the four mixtures are relatively low, thanks also to the use of natural gas as fuel type in the dryer combustion process;
- **Particulate**: In this case, the decrease in stack emissions is not so clear. The average shows a 7% in reduction using WMA, but the particulate emissions are mainly related to the aggregate dust, so, probably, their reduction is not so much dependent on the temperature change;

- **SO_x**: Sulphur oxide show a slight reduction of 6,5% and it is mainly related to the sulphur content in the fuel type and, as a consequence, they will be partially linked to changes in temperature. However, even the oxygen content during the combustion process can influence its production;
- **CO**: Carbon monoxide represents an exception: the results show an increase in its concentration of 11% by using WMA compared to HMA. It is not only linked to the temperature change, but also to the combustion process, specifically to a shortage of Oxygen content during the process, which allows a fast increase in CO (incomplete combustion). So, production of CO is mainly dependent on the burner tuning and maintenance.

In Chapter 3, Section 3.2.1, the stack emissions have been estimated started from the energy consumption (MMBtu/ton) to produce the asphalt mixture, multiplying by the emission factors EFs related to the use of natural gas: using this kind of method but applied just to the estimated energy saving of the Italian case study, depending on a reduction of temperature of 40°C = 71°F (1,100 Btu/°F/ton * 71°F * 10⁻⁶ = **0.078 MMBtu/ton**), it will be possible to obtain directly a sort of **Δg/ton estimated**, to compare with the one measured reported in **Table 36**.

Example of calculation for the emission saving going from WMA to HMA with ΔT = 40°C=71°F:

- being the energy saving: 0.078 MMBtu/ton = **0.083 GJ/ton**;
- being the NO_x EF = **74 gNO_x/GJ**;

NO_x saving will be: 0.083 GJ/ton * 74 gNO_x/GJ = 6.14 g NO_x/ton reduced.

Applying this method to the other pollutants, the following Table will be obtained, in order to compare *Δg/ton calculated* and *Δg/ton measured*:

Emission [g/ton]	Δ g/ton measured	Δ g/ton estimated
Particulate	0.23	0.13
CO	-31.72	2.41
NOx	3.04	6.14
SOx	2.26	0.06
VOC	0.62	1.99

Table 39. Comparison between the emission difference measured and estimated.

As expected, of course some differences in these results are observed: indeed, in the estimate calculation is clearly applied a theoretical approach to obtain the amount of emissions directly related to the fuel combustion, assuming a sort of ideal and complete combustion process in the dryer. In this way, it has been possible to define the benefit related to the difference in temperature, but without considering all the possible influencing factors that can change the amount of reduction Δg/ton measured in a real case study (oxygen rate, burner tuning and maintenance, cleaning and equipment efficiency, WMA additive influence...).

Nevertheless, although this influence, even through these direct measurements is found a general reduction in average WMA emissions compared to HMA ones (except for CO), demonstrating a lower environmental impact for the warmer technology.

6.2 Possible estimations on the basis of the real case study

6.2.1 GHG emissions estimation

On the other hand, concerning the greenhouse gas emissions, direct measurements were not gathered in the Italian case study and the energy usage for production is not known.

However, through the acquaintance regarding the NCHRP Project 9-47A [25] in Section 3.1.1, it is possible to estimate the energy saving MMBtu/ton considering directly the reduction in temperature of 40°C (= 71°F) producing WMA. After that, involving the use of natural gas as fuel type and using the corresponding Emission Factors, the emissions connected to this energy saving will be calculated.

The emission factors EF related to GHG emitted using natural gas are respectively [28]:

- CO₂ = 56100 mg/MJ;
- CH₄ = 1 mg/MJ;
- N₂O = 0.1 mg/MJ.

While, to estimate the saving linked to $\Delta T = 71^\circ\text{F}$ it is used the empirical relationship *Energy Saving = 1100 Btu/°F/ton* [25].

Knowing that $1 \text{ MMBtu} = 1000000 \text{ Btu} = 1055.05 \text{ MJ}$ it will be obtained:

Energy saving $\Rightarrow 1100 \text{ Btu/}^\circ\text{F/ton} * 71^\circ\text{F} = 78100 \text{ Btu/ton} = 0.078 \text{ MMBtu/ton} = \mathbf{83.35 \text{ MJ/ton}}$.

Now, multiplying this energy saving value [MJ/ton] to each of the GHG emission factors [mg/MJ], the emissions saving will be estimated [mg/ton] related to 71°F (40°C) reduction in mixing temperature. The emissions saving results are gathered in **Table 38**:

GHG	Emissions Saving (HMA vs WMA) with $\Delta T^\circ\text{C} = 40^\circ\text{C}$
CO₂	4.67 kg/ton
CH₄	83.35 mg/ton
N₂O	8.34 mg/ton

Table 40. Reduction in GHG production with $\Delta T = 40^\circ\text{C}$.

These results are very significant in terms of impact and carbon footprint. Specifically, the reduction in carbon dioxide, in line with what is found in literature [29, 39], with a decrease higher than 4 kg per ton of mixture produced. Considering for example an average plant operational potential of 165 ton/h, it means that in one hour it can be achieved a CO₂ saving of 770,55 kg producing WMA instead of HMA.

6.2.2 Load-out and Silo filling estimation

Moreover, on the basis of the acquaintances gathered in this work thesis, even the potential Load-out and Silo-filling emissions could be estimated for this Italian case study, knowing the mixing temperature of both WMA and HMA to be respectively 130°C (267°F) and 170°C (338°F).

Indeed, the Predictive Emission Factor Equations (Section 4.3, **Tab.24**) in function of the production temperature and the asphalt volatility of the mixture can be used, using a value of volatility equal to $V = -0.03\%$ related to the bitumen use in this Italian case study.

It will be obtained:

	Load-out Emission Factors			Silo filling Emission Factors		
g/ton	WMA	HMA	% Reduction	WMA	HMA	% Reduction
Total PM	0.084	0.095	11 %	0.15	0.16	6.25 %
Organic PM	0.002	0.013	84 %	0.0015	0.0095	84.2 %
TOC	0.024	0.16	85 %	0.072	0,45	80 %
CO	0.0082	0.05	82.6 %	0.007	0,044	84.6 %

Table 41. Load-out and Silo filling emissions estimation for the italian case study.

It's really interesting to observe the results obtained with these calculations: there is a clear average emissions reduction by 83 % using the warm technology instead of the hot one, maintaining a mixing temperature difference of 40°C.

The only exception is represented by the total PM, characterized by a reduction of 11 % in load-out emissions and only 6,25 % in silo filling ones. Indeed, even in this case, it can be linked to the fact that the total PM is mainly inorganic and it is not so much affected by temperature changes.

So, also in these asphalt plant operations has been possible to define the environmental benefit of using the Warm mix asphalt to replace the conventional Hot mix asphalt technology.

Unfortunately, as seen in Chapter 5, it is not yet possible nowadays to find a theoretical way to estimate even the emission during paving operations at the worksite. However, the laying-down temperature of WMA and HMA mixtures in this Italian case study is respectively about 120°C and 160°C, and it is possible to imagine a significant reduction in fumes exposure, dealing with this great difference in temperature.

Conclusions

According to the development of a “Sustainable growth”, based on a reduction in raw materials consumption and process emissions, in the asphalt production field this approach is described by the research toward different adoptable technologies less impacting from an environmental standpoint.

The present work-thesis has the objective to define the potential environmental benefits of Warm Mix Asphalt in terms of energy consumption and in particular regarding airborne pollutants and GHG emissions, focusing on its comparison with the reference Hot Mix Asphalt mixture. In order to achieve this goal, this thesis will go into detail through specific and reliable real case studies and, when possible, find some estimation method to apply in generic situations and boundary conditions.

The research has deepened the problem of pollutant emissions related to “asphalt concrete operations”:

this term refers to all the process steps, from the production at the plant (dryer drum, load-out and silo filling emissions) to the laying-down and compaction stage (road paving).

- Dealing with the *dryer-drum* impact, this step is characterised by a combustion process aiming at drying and heating the aggregate. Both the analyses have been carried out concerning the potential energy saving and reduced emissions using WMA. It has been found that, going from HMA to WMA production, the average energy saving will be of about 22.1 %, considering an average difference in temperature of 27°C (48°F). Stack emissions (NO_x, Sox, CO, PM, VOC, N₂O, CH₄, CO₂), which are mainly connected to the fuel consumption in this combustion process, show a regular reduction of about 20 % using WMA. Moreover, in terms of carbon footprint reduction, it is important to put the emphasis on the CO₂ reduction with a saving of 3.22 kgCO₂/ton.
- Regarding *load-out* and *silo filling* emissions considering a mixing temperature of 157°C and 130°C respectively for HMA and WMA, it is estimated an average emissions reduction (Total PM, Organic PM, VOC, CO) by 70 % going from HMA to WMA. The only exception is related to the total PM, probably because it is mainly inorganic and so less affected by temperature difference.

- The final stage concerns the *road paving* operations: the spreading and compaction of the mixture of course are considered to be sensitive even for the workers exposure. However, it results very difficult to obtain reliable collected data about this operation impact, depending on several variables such as weather, sampling process, paving crew, equipment, construction logistics and workers role and position. Nowadays, it is not present yet a theoretical method to estimate this kind of emissions.

The last Chapter 6 is based on the application of all the concepts developed in this work-thesis to an Italian real case study and it has been obtained confirmation regarding the lower environmental impact in using WMA. The measured reduction in stack emissions has been compared to the estimated one (using the theoretical procedure in Chapter 3) observing some differences: indeed, in the theoretical approach all the influencing variables present in a real case study are not considered. Regarding the GHGs estimation, a significant reduction of 4.67 kgCO₂/ton has been found using WMA. The final step has developed the estimation of load-out and silo filling emissions using the Predictive Equations, applying a mixing temperature equal to WMA T°C = 130°C and HMA T°C = 170°C. It can be observed a clear average emissions reduction by 83 % using the warm technology, except for the Total PM that is mainly inorganic.

So, such findings demonstrate the potential of warm technology for reducing pollutant emissions concurrently providing significant energy savings, and improving the health conditions for workers: these results surely help to better appreciate some potential drawbacks of WMA mixtures, thanks to the positive contribution in terms of environment. Of course, in the future, a wider series of measurements and more detailed formulas validation will be done, considering other real case studies, and a better way to analyse road paving emissions will be found, even improving the conventional Emission Factors Database.

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