MULTIVARIATE DATA ANALYSIS APPLIED IN HOT-MIX ASPHALT PLANTS

Régis Sebben Paranhos[1], *Carlos Otavio Petter*[2]

[1]*Federal University of Pampa (Unipampa), Mining Technology Department, Caçapava do Sul, Brazil*
[2]*Federal University of Rio Grande do Sul State, Mining Department, Porto Alegre, Brazil*

ABSTRACT

A Multivariate data analysis was used with environmental data obtained from Hot-Mix asphalt (HMA) plants. The main objectives of the study were to describe and interpret the real "phenomena" that exist on HMA plants; also, to search for the best mixing conditions. There is not only one parameter to be controlled and checked when HMA are being produced. In this context, a multivariate data analysis was carried out, and the main control parameters considered for prediction and regression analysis were HMA formula, fuel type, asphalt temperature and rate of production. "Global warming emissions", "organic emissions" and "energy consumption" were chosen as models of regression. Globally, plants powered by natural gas emit half the amount of CO2, nine times less NOx and eighteen times less CO than plants with fuel oil. For organic emissions, if the asphalt temperature increases, TOC emissions are increased; however, if the rate of production increases, TOC emissions are decreased. The main conclusions in regards to the means with which HMA plants can be designed and operated in better ways were: the manufacturing of hyper-mobile and small HMA plants as opposed to stationary large plants, and the use of burners with natural gas instead of fuel oil in all cases. The production of HMA plants, aiming at a cleaner production, means to operate HMA plants always considering timespan in the long term. This encompasses undertaking dayly, weekly and yearly analyses.

Keywords: Greenhouse gases, Organic emissions, Energy consumption, Hot-Mix Asphalt process, Multivariate data analysis

1. INTRODUCTION

This paper presents a multivariate data analysis dedicated to Hot-Mix Asphalt (HMA) plants, focused primarily on emissions and energy consumption. This statistical tool was used taking into account the complexity of the process and the number of control parameters [1]. Concerning the environmental data used, it was necessary to treat them previously according to a specific methodology [3]. According to such methodology, the only environmental data used was that issued on stabilized periods of combustion in HMA plants. Statistical software1 was used for all analyzes. It is important to highlight the inexpressive number of environmental data on emission issues from HMA plants.

2. OBJECTIVES OF THE STUDY

The main objective is to analyze the influence of operating parameters on airborne emissions and assess global warming potential and organic emissions. Another important objective was to search for the best mixing conditions, i.e. production with less energy and less emissions, and propose means with which Hot-Mix asphalt plants can be designed and operated in better ways. In this context, a multivariate data analysis has been used as a support tool, especially in: data description, discrimination and classification, interpret the real "phenomena", regression and prediction and validating the pre-treatment of data carried out before any analysis.

3. METHODOLOGY USED

3.1 *Background of environmental data*

3.1.1 Process approach

This study was carried out in relation to the HMA manufacturing conditions and the formulas. It was initially necessary to identify the main elements to study, together or separately, the parameters at the entrance and exit and in the mixing zone. From the environmental aspect, the HMA Plants (Drum Mix process) can be represented by five parts, as pointed out on Figure 1. The parts that are numbered for clarity purposes are as follows: (1) energy, (2) material resources, (3) coating process, (4) manufactured HMA and (5) emissions to the atmosphere. HMA plant's emissions are not constant over time. There are fluctuations due to the process used, under or out of control [4]. Among the out of control fluctuations, we can mention the moisture of the aggregates, which is entirely dependent on the storage and the meteorology, and the fuel variations (public network). However, even the parameters considered as a priori under control are subject to the variations resulting from the needs of the road construction site [5]. It is the case of production rate, input materials regularity and HMA temperature.

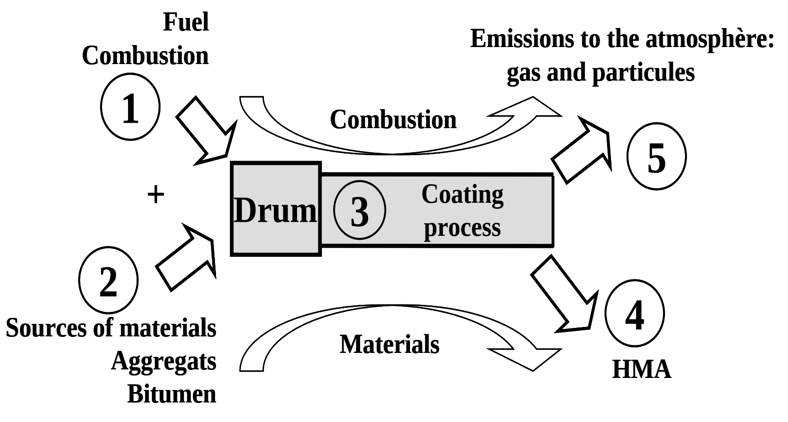

Figure 1 – Main axes of study: combustion and materials

Consequently, during production, combustion must be adapted to many variations: the fume emissions temperatures, the HMA and the gaseous emission volume change over time.

---

[1] Unscrambler® 9.2, English version, copyright© 1986-2005 CAMO PROCESS AS.

3.1.2 Environmental data

The database measures of airborne emissions and control parameters used in the present multivariate analysis have been obtained in two HMA Plants located in France and selected according to previous methodology. More details are described by Paranhos [3][10]. In this context, an experimental full scale tests have been undertaken to characterize a parallel mix flow process in order to collect several environmental data linked to asphalt production. For industrial conditions, only few types of equipment and labor have been employed in order to collect environmental data linked to asphalt production.

3.2 *Description of the main parameters*

In a HMA plant, the parameters that may be directly controlled by the operator of the plant at the command cabin are: production rate, bitumen temperature, negative pressure of the drum (burner flow rate) and natural gas consumption (or oil). The adjustment of the pressure in the burner and the HMA temperature are indirectly controlled by means of the controllable parameters [5]. The raw data obtained were gathered and expressed either in concentration versus time or in flow. Aiming at improving the correlation of regression and global accuracy, the indicators (ICO/CO2) and the ambient air temperature (AirT) have been added as parameters of plant control.
In the case of the HMA process studied, considering that there are several variables, it was necessary to choose only the most important ones. Therefore, a Principal Component of Analysis (PCA) was carried out aiming at selecting which variables could be discarded [6].

3.3 *Multivariate Analysis*

3.3.1 Principal Component Analysis (PCA)

The purpose of all multivariate analysis is to decompose the data in order to detect and model the "hidden phenomena" [4]. The concept of variance is very important here. It is a fundamental assumption in multivariate data analysis that the underlying "directions with maximum variance" are more or less directly related to these phenomena.
Frequently, there are parameters that can be taken out of analysis. They do not have much importance for future statistical analysis and may cause some perturbations on the results. On the other hand, if there are groups of data with different characteristics, they should be analyzed separately [1].
Prediction was carried out aiming at assessing global warming, organic emissions and energy consumption (Figure 2). Model A is related with greenhouse gas emissions (linked to global warming), represented by CO2, CO, SO2 and NOx emissions. Model B is related with organic emissions such as TOC, CH4 and PAH. Finally, model C is related with energy consumption, represented by fuel consumption.

3.3.2 Regression and prediction

After PCA, a multivariate calibration (PCR/PLS2) was carried out. The aim in this step was to understand emissions and energy consumption focused on control parameters previously determined by PCA. This involves two sets of data, X and Y, by regression. Firstly, a multivariate regression model of the (X,Y) relationship must be established. The statistically correct way to describe this is to estimate the parameters of the (X,Y) regression model. The regression model is secondly used on a new set of X-measurements for the specific purpose of predicting new Y-values (Figure 3).

---

[2] PCR: Principal Component Regression and PLS: Partial Least Square Regression

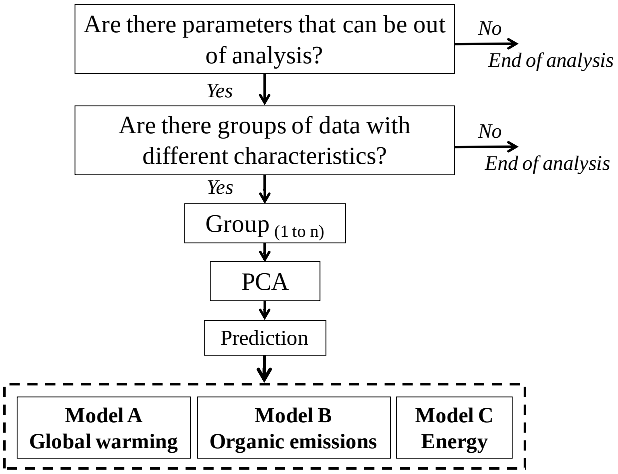

Figure 2 – Prediction methodology

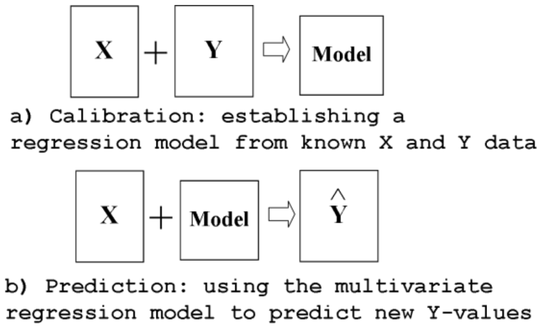

Figure 3 – Calibration and prediction stages

In PCR/PLS predictions, new X-data are projected into the model components. Y usually estimates these projected scores and loadings matrices, T and P. The traditional regression equation is Y=b0+b1x1+b2x2+…+bnxn. The reason is that this makes it possible to use only X-measurements for future Y-determination, instead of making more Y-measurements. Typically, the Y-measurements may be expensive, labor intensive, time consuming, dangerous. It would be desirable to replace them with X-measurements if these are simpler, cheaper, and faster, as with Hot-Mix asphalt plants.

3.3.3 Partial Least Squares Regression (PLS-R)

The control parameters are used as X matrix in the model of regression. They are the parameters that must be chosen by the operator when starting production. Then, three models of prediction (Y matrix) have been proposed. In the calibration stage of PCA, considering that it is necessary to detect and remove any collinearity existing on the database, only the control plant parameters have been kept, maintaining, however, the same behavior and previous characteristics. At the final stage of the treatment with environmental data, 70% of the phenomena could be explained by PC1 and PC2. This result is better than the initial approach, in which only 61% was explained by PC1 and PC2. Figure 4 shows the final parameters used in regression models.

X	Y		
Control parameters	Model A Global warming	Model B Organic emissions	Model C Energy
Formula Fuel type (F) Period (P) Burner flow rate (BFR) Negative pressure of the drum (NPD) Air temperature (AirT) Asphalt temperature (AT) Rate of production (RP) Moisture of aggregates Fumes temperature (FT) Bitumen temperature (BT) Bitumen flow (BF) Quality of combustion (I)	CO2 SO2 CO NOx	TOC CH4 PAH	Fuel consumption (FC)

Figure 4 – Model parameters of regression (PLS-R)

4. PRINCIPAL RESULTS

According to the methodology proposed, the three models of prediction give for each fuel burned the following principal conclusions taking into account the coefficients of correlation.

4.1 *Global warming*

For this model, plants powered by natural gas and under controlled conditions of production can be represented by CO2, NOx and CO emissions. Rate of production (RP), in tones/hour, is the most important parameter linked with global warming emissions. In general, emissions grow with the rate of production. What is most important here is that asphalt temperature (AT) is not a very important parameter for global warming in HMA plants. The coefficient of correlation of 0.97 was considered very good.

4.2 *Organic emissions*

For total organic compounds (TOC), rate of production (RP) and bitumen temperature (BT) are the principal parameters. In this case, for an increase in rate of production (RP) there is a decrease in TOC emissions. Also, the coefficient of 0.99 was considered excellent.

4.3 *Possibility of prediction*

The coefficients of regression calculated allow the quantification of the most important parameters of plant control, i.e. the “real phenomena”. These results show the parameters that should be more controlled during production and, on the other hand, the parameters with less importance for control. In terms of correlation, the prediction is pretty good for tests powered by fuel gas. This result is very coherent, taking into account the dedicated conditions of production (Figure 5). On the other hand, the coefficients of correlation are not good (about 0.70) for tests with fuel oil that were obtained with industrial conditions of production (Figure 6).

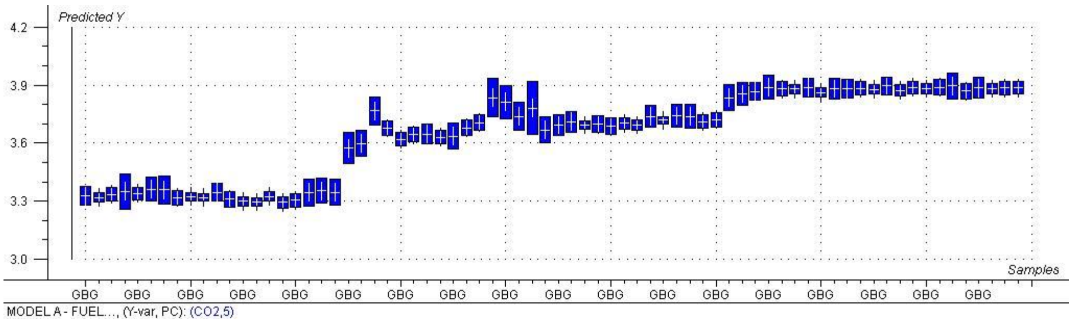

Figure 5 – Predictions and standard deviations for CO2 (fuel natural gas)

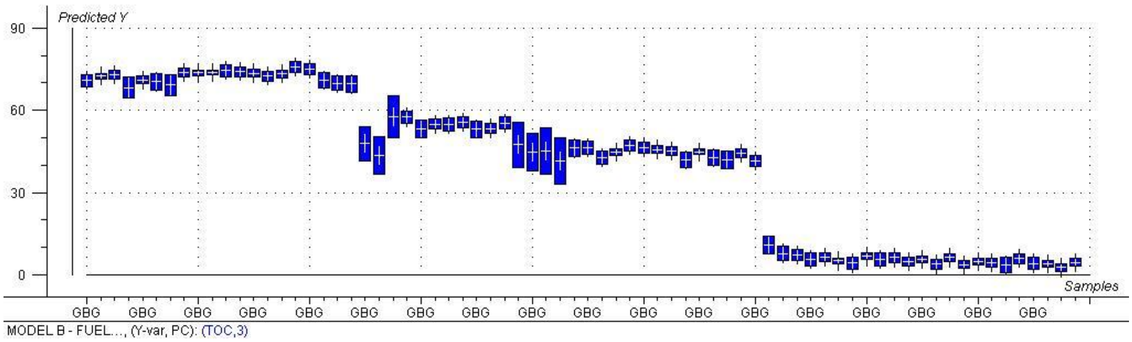

Figure 6 – Prediction and standard deviations for TOC (fuel natural gas)

4.4 *Best mixing conditions: cleaner production*

In this study, the best mixing conditions mean having a production with minimized emissions of greenhouse gases and organic residue, besides low energy consumption. As a first approach, responses can be obtained by interpretation of tendencies between analyzed parameters.

4.4.1 Greenhouse gases

Globally, plants powered by natural gas emit half as much CO2, nine times less NOx and eighteen times less CO than plants with fuel oil;

- For fuel natural gas, considering NO_x and CO_2 emissions, small plants are preferable over big plants, taking into account that a high rate of production (ton/h) increases emissions. On the other hand, if asphalt temperature increases, NO_x and CO_2 emissions are reduced;
- For fuel oil, only temperatures are important parameters for CO_2 emissions control.

4.4.2 Organic emissions

Generally, if temperatures increase, TOC emissions are increased; however, if the rate of production (RP) increases, TOC emissions are decreased. However, for Polycyclic Aromatic Hydrocarbon (PAH) emissions there is no continuous emission data for definitive interpretation [7].

4.4.3 Energy consumption

- For fuel natural gas, fumes temperature (FT) and negative pressure of drum (NPD) are the most important parameters. Both are linked with the burner and its adjustments: the air out of control has an important role on consumption;
- For fuel oil, both burner flow rate (BFR) and asphalt temperature (AT) are linked with fuel consumption, with the same importance. In this case, when temperatures or rate of production (RP) are increased, fuel consumption is also increased.

4.5 *Means to design and operate Hot-Mix asphalt plants in better ways*

In the last 30 years, the design of HMA Plants has pointed to the development of more environmentally efficient plants [5]. Some innovations and new processes have been developed, such as counter-flow process and double or triple drum mixer. These innovations were important, but not sufficient to improve cleaner production in all sectors. Actually, the innovations were concentrated only on devices linked with economic results. This study explained that rate of production, frequent starts and stops, overall temperatures and other parameters have an important role when the global context is analyzed. Another major problem for researchers in these industrial segments is that there is no available environmental data for analysis, and innovations are restricted to plant makers.

In this context, considering the results obtained in this study by multivariate data analysis, the design of HMA plants, taking into account a cleaner production, should foresee:

- The manufacturing of hyper-mobile and small HMA plants in opposition to stationary large plants;
- The use of burners with natural gas instead of fuel oil in all cases;
- The maintenance of combustion in the burner at the best conditions and permanently regulated.

Likewise, the operation of HMA plants aiming at a cleaner production means to design HMA having a longer time-span perspective, in the place of a short term view. This implies a daily, a weekly and a yearly analysis. Therefore, the following items are necessary:

- Produce with low rate of production;
- Low bitumen temperature – it is indispensable to develop new formulas for asphalt with medium temperature (up to 120ºC);
- Regular production to avoid peaks of production and unnecessary starts and stops;
- Production in the morning (when ambient temperature is cooler) or in the afternoon (hotter) present different conditions for environmental analysis, and it becomes interesting to run the production taking into account the best period of production (P);
- Develop the culture of employing heated stocks, thus regulating and reducing impacts.

5. DISCUSSION OF MULTIVRIATE DATA ANALYSIS

Many histograms show the great difference between environmental data obtained with different fuels: natural gas or oil. The histogram of CO2 emissions shows that emissions for fuel gas and oil are, respectively, 3.6% and 6.4%. The same behavior exists for other emissions, such as CO, NOx and TOC. It is possible that there are other groups linked with the fuel type used. Therefore, for future statistical analyzes and environmental approaches it is necessary to study these groups separately, as recommended by Striple [11].

5.1 *Full data analysis*

Scores plot: The first important information provided by PCA is that there are two groups and eight subgroups in environmental data to be analyzed, issued by different fuels and different tests. Clusters or groups of objects do not always imply problems, but if such groups are clearly separated, a model might be necessary for each group separately, as fuel natural gas or oil (Figure 7). Objects close to each other are similar; those far away from each other are dissimilar. Isolated objects may be outliers[3]. In the present plot, the samples are well spread in PC1 and PC2, suggesting that there are not many outliers. This important result highlights the good accuracy of the PCA carried out and points to good future predictions.

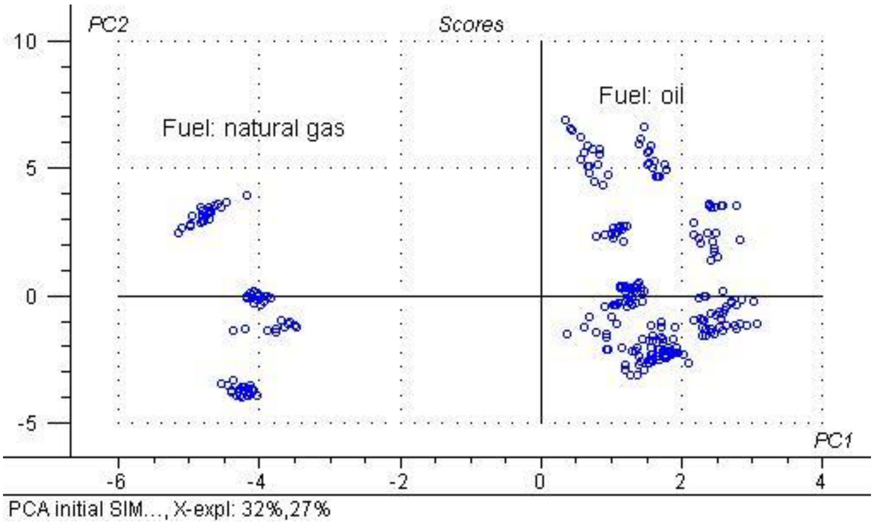

Figure 7 – Scores plot of full data

Loadings plot: In loadings plot, variables with a high degree of systematic variation typically have large absolute variances, and large loadings. They lie far away from the origin, and variables of little importance lie near the origin. In this HMA study, there are many variables near each other, meaning high correlations between variables. In this first stage of analysis, only electrical consumption has been considered a parameter without importance for PC1 or PC2, and would be out of future refined analyzes. In the sequence, other variables highly correlated with each other may be removed from analysis.

5.2 *Data analysis of natural gas*

Scores plot: In the sequence, the data of fuel gas and fuel oil were analyzed separately according to the first results shows a PCA overview taking into account only data of production using fuel natural gas. In scores plot, there are four groups clearly identified representing four tests with different rates of production and temperatures. Concerning outliers, they would not be taken into account considering that the data were obtained at a stabilized period of production.

Loadings plot: In loadings plot, the proximity between variables is another important aspect; the correlation increases with proximity: bitumen temperature, total organic compounds, oxygen level and carbon monoxide are highly correlated. On the other hand, variables symmetrically opposite with respect to a PC axis have inverse correlation, such as CO_2, NO_x and ambient air temperature.

Explained variance
Taking into account only the plant powered by fuel natural gas, 91.5% of the phenomena are explained by PC1 and PC2. This excellent result is no surprise, because the data were obtained in dedicated conditions of production (stabilized data).

---

[3] Outliers: atypical objects or variables on a few occasions. If outliers are the result of erroneous measurements, of if they represent truly aberrant data, they should be removed [1].

5.3 *Data analysis of fuel oil*

Scores plot: The data were obtained with industrial conditions of production and many outliers were detected and put out of analysis, contributing to reduced noise and to increased explained variance. Typically, several formulas can be made in one day of production. In the database studied, there are three groups of variables representing three formulas manufactured: GB (Grave Bitume), BBSG (Béton Bitumineux Semi-Grenu) and BBTM (Béton Bitumineux Très Mince) according to the French catalog [9, 12].
Loadings plot: Despite the fact that only 65.6% of the phenomena were explained by PC1 and PC2, there is no surprise, because the data were obtained in industrial conditions of production. Bitumen temperature is mostly linked with PC2. On the other hand, moisture of aggregates is inverse in correlation with fuel consumption on PC1 axes.
Explained variance: Taking into account only the plant powered by fuel oil, 65.6% of variance are explained by PC1 and PC2, and 95.2% are explained by all PCs until PC6.

6. CONCLUSIONS

This study is based on a sustainable development context applied to road infrastructure in order to contribute to environmental preservation. More precisely, Hot-Mix Asphalt emissions were studied on two similar HMA Plants (mobile and fixed units), with different fuels: oil and natural gas. As far as the influence of production conditions are concerned, the kind of manufactured formulas and the period of production, a multivariate data analysis was carried out.
On a HMA plant, an analysis and processing of data methodology allowed to identify conforming and stabilized data at combustion level. That methodology was applied in usual and special manufacturing conditions in order to evaluate the emissions and to determine/predict concentration intervals associated to the different production conditions. Then, the production with less energy consumption and fewer emissions was identified in order to point to the means with which Hot-Mix asphalt plants could be designed and operated in better ways.
In general, for fuel gas, 89% of the phenomena could be explained by PC1 and PC2, the two main components of the analysis. On the other hand, when fuel oil was burned, PC1 and PC2 could explain at most 60%.
Plants powered by natural gas emit half the amount of CO2, nine times less NOx and eighteen times less CO than plants powered by fuel oil. Especially for NOx and CO2 emissions, small plants are preferable over big plants, taking into account that high rates of production increase emissions. On the other hand, if asphalt temperature increases, NOx and CO2 emissions are reduced. For fuel oil, only temperatures are important parameters for controlling CO2 emissions. Organic emissions are increased when temperatures are increased together. However, if the rates of production (RP) increase, TOC emissions are decreased.
The main means with which Hot-Mix asphalt plants can be designed and operated in better ways are: the manufacture of hyper-mobiles and small HMA Plants in opposition to stationary large plants; the use of burners with natural gas instead of fuel oil in all cases; to produce with low rate of production and low bitumen temperature; to produce regularly in order to avoid peaks of production and unnecessary starts and stops; it is also interesting to run the production taking into account the best period of production and to foster a culture of employing warmed stocks. Finally, this study shows that it is possible to estimate with very good accuracy emissions and energy consumption in HMA plants using usual parameters of control, predicting the best mix conditions of production.

7. ACKNOWLEDGEMENTS

We would like to thank Dr. Paulo Conceição, researcher at LAPROM/UFRGS, for providing technical advice and data for case studies throughout this research, and the CNPq of Brazil for Régis Paranhos' financial support (Post-doctoral PNPD research grant).

8. REFERENCES

1) Esbensen K. H., *Multivariate Data Analysis – In practice.* ISBN 82-993330-2-4 CAMO ASA, 4ª edition 2000.
2) Varga M. and Kuehr R., Integrative approaches towards Zero Emissions regional planning: synergies of concepts. Journal of Cleaner Production 15 (2007) 1373 – 1381. Doi: 10.1016/j.jclepro.2006.07.009.
3) Paranhos, R.S. Centrales d'Enrobage – Approche multi-échelle des émissions d'un procédé d'élaboration des enrobés à chaud. Éditions Universitaires Européenes, 2010. ISBN 978-613-1-54591-7.
4) Paranhos R, Monéron P., Jullien A, de-La-Roche C et Sautet JC. Etude de la combustion dans une centrale d'enrobage. 17ème Congrès Français de Mécanique, 2005.
5) Monéron P. Économies d'Énergie sur Centrales d'Enrobage. Rapport du Laboratoire des Ponts et Chaussées, 74p., France, 1993b.

6) Rydh C.J., Sun M., Life cycle inventory data for materials grouped according to environmental and material properties. Journal of Cleaner Production, Volume 13, Issues 13-14, November-December 2005, Pages 1258-1268; doi:10.1016/j.jclepro.2005.05.012.
7) Ventura A., Monéron P., Jullien A. Polycyclic Aromatic Hydrocarbons emitted from a hot mix asphalt process: study of the influence of recycled bitumen use, Journal of Environmental Engineering and Science, Vol. 6, No. 6, 2007b, pp. 727-734.
8) EPA (U.S. Environmental Agency). Office or Air Quality Planning and Standards. Emission Measurement Center. Research Triangle Park, NC 27711. Emissions Factor Documentation for AP-42. Hot-Mix Asphalt Plant. Final Report, 49 p., Feb 2004.
9) SETRA – Guide technique- Conception et dimensionnement des structures de chaussées. Ed LCPC-SETRA, Paris, December 1994.
10) Jullien A., Monéron P., Quaranta-Millet G and Gaillard D., Air emission from pavement layers composed of varying rates of reclaimed asphalt. Resources, Conservation & Recycling, Vol 47, 2006, pp 356-374.
11) Stripple H., Life cycle assessment of road. A pilot study for inventory analysis. Rapport IVL Swedish Environmental Research Institute, 2001, 96p. and annex.
12) AFNOR NF EN 13108-21. Mélanges bitumineux, spécifications des matériaux – partie 21 – contrôle de la production en usine, 2006.
13) Kriech J., Kurek J., Wissel H, Effects of mode of generation on the composition of asphalt fumes. Asphalt Institute - Executive Offices and Research Center, 1992 (at http://www.asphaltinstitute.org/ai_pages/FAQs/Environmental_FAQs.asp).