Study of tunnel pavements behaviour in fire by using coupled Cone Calorimeter – FTIR analysis.

Puente, E (puentee@unican.es)[a*]; Lázaro, D. (lazarod@unican.es)[a]; Alvear, D. (alveard@unican.es)[a].

[a] GIDAI Group – Fire Safety – Research and Technology, University of Cantabria, Ave. Los Castros, s/n; 39005 Santander (Spain), Telf.: +34942201826, Fax : +34942202276

Abstract

In recent years there has been a growing interest in analyzing the contribution of pavements to fire growth for improving safety in tunnels. However, only few analyses take into account or quantifying toxic gases emitted during the pavement burn out. In this study, simultaneous cone calorimeter and FTIR analyses were conducted to evaluate the contribution to fire growth of two different types of fireproof pavements (concrete and asphalt) obtaining averaged values of heat release rate per unit area of 0 and 50 kW/m^2 respectively. The CO released was monitored as a valuation of how complete is the combustion taking place and also to compare the toxic potential of such materials. Further approximated ignition temperatures of asphalt in the range of 420-450 ºC were also obtained. The results indicate that concrete pavement do not contribute to fire growth since no ignition was observed while asphalt pavement contributes similarly to other components generally found in vehicles. Very opaque fumes with significant concentrations of CO were detected during asphalt pavement combustion. Severe thermal degradation was observed in the asphalt pavement samples, including calcination and the detachment of aggregates while on the surface of concrete pavement samples just some minor cracks were reported.

Keywords: Tunnel fires, Pavement performance, Heat release rate, FTIR.

1. Introduction

When a fire is developed most of the materials involved contribute to the fire growth and release toxic effluents as proper compounds via gasification as well as compounds derivate from chemical combustion. In buildings and infrastructures, especially in confined fires like tunnel fires, this aspect get special relevance because of the depletion of oxygen (O_2) and related to it the presence of carbon monoxide (CO) and other toxic effluents depending on the nature of the materials in combustion. This issue constitutes the first cause of death in tunnel fires [1].

Road tunnel fires have shown a chaotic and dangerous situation, resulting in several human loss and injuries and considerable damage to property [1], [2], [3], [4]. Depending of the geometry of the tunnel (cross section, length etc.) an intolerable atmosphere for people can be generated in a short period of time, due to the thermal condition, the lack of oxygen and the confined space. The fumes produced during the fire, which include solid and liquid particles, constitutes a frequent cause of severe intoxication; impede the renewal of oxygen inside the tunnel and difficult the evacuation process due to reduced visibility [1].

Traditionally, fire safety in tunnel have been focused on evacuation, smoke extraction and maintain the structural integrity of tunnel linings, leaving aside the role of the contribution of pavements to the fire development. However, in recent years there has been a growing interest in analyzing the contribution of pavements to fire growth to improve safety in tunnels and some research and studies has been carried out [1], [5], [6], [7], [8].

Furthermore, several studies have analyzed the toxic gases resulting from burning vehicles or the equipment installed in the tunnel, but limited analysis takes into account the toxicity generated by the burning of tunnel pavement [1], [9], [10], based mainly on FTIR technique dynamic analysis.

Tewarson [11] has found a correlation between the average smoke emission rate ($\dot{G}_s$) and the chemical heat release rate times the ratio of the emission rates of CO to CO2. The correlation holds for particulate dominated smoke and for fuels with non-particulate dominated smoke in the presence of H and OH atoms provided by other fuels or by the ignition source, such as a hydrocarbon gas burner. Suzanne et al. [12] use a smoke parameter, that is the ratio of the amount of smoke produced divided by the heat released per gram of pyrolysing material. The product of the smoke parameter and a fire growth parameter is proportional to the SMOGRA [13] which represents the smoke production rate. The fire growth parameter is the relation between the square of the maximum heat release rate per unit area and the ignition temperature time determined in the Cone Calorimeter.

Generally, pavement solutions for tunnel construction consist of cement concrete and common compact asphalt. Of these, cement concrete is a non combustible material and there is not any evidence that limited its use in tunnels [14]. On the other hand asphalt pavements can ignite at temperatures as low as 330 ºC [15] contributing to increase the fire burning rate and experiments thermal degradation [1], [14], [15]. However, in most cases, these effects are ignored [10] since experimental results indicates that asphalt pavement would be likely to contribute less than 20 % of the heat released from the primary combustion source, if sustained ignition is achieved [7].

Several test methods have been used to characterize the fire behaviour of pavements which includes radiant panel flooring test (EN ISO 9239-1 [16]), cone calorimeter test (ISO 5660-1 [17]) and some others [1]. However some of them are of limited use due to the magnitude of the imposed radiant heat level [7] or due to a lack of extrapolating the results to a real fire situation in tunnels [18].

In the present study, coupled cone calorimeter and FTIR analysis was employed to assess dynamically the contribution of two different tunnel pavement materials (concrete and asphalt pavement) to fire growth and the toxic gases generated. From these measurements a characterization of volatile products release behaviour was obtained as well as detailed information regarding the fire behaviour of materials analyzed.

2. Experimental Setup

The test apparatus consists of a cone-shaped radiant electrical heater, a load cell, a hood and duct system and gas analysis and mass flow instrumentation. The irradiance level of the heater is maintained at the selected level by mean of previous calibration tests by methane burner with a mass flow controller which allows the fine tuning of heat release rate.

Gases and combustion products released from the burning specimen are collected in a hood that feed a horizontal exhaust dust. Between the hood and the duct is located a restrictive orifice to promote mixing and to guarantee that all volatile species are completely diluted in air. The resulting gas is sampled to quantify the volume percent of oxygen, carbon dioxide and carbon monoxide passing the gas into three gas analyzers.

The heat release rate of the material analyzed is then calculated applying the principle that heat release rate is proportional to the oxygen consumed during combustion. Several other parameters are also obtained from the results including but not limited to ignition time, peak heat release rate, total heat release, mass loss and mass loss rate, effective heat of combustion, rate of smoke production, etc.

The concentration of the different gas species has been analyzed using Fourier Transform Infrared Spectroscopy (FTIR) [19], based on the principle that each functional chemical compound has a characteristic absorption frequency. The infrared absorption spectrum is unique to all different gas molecules so it is possible to identify any gas component from its IR spectrum. For the analysis, a Gasmet CX spectrometer was used, allowing the identification and quantification simultaneously of multiple gaseous compounds among which are (NO, NO_2, SO_2, CO, CO_2, H_2O, CH_4, C_2H_4, C_3H_6, C_3H_8, HCl, NH_3, HF etc.).

The equipment consists of an infrared source, the interferometer, the sample cell, a detector and a signal processing unit. The IR source produces a broad band of IR radiation which is modulated in the interferometer. The modulated radiation passes through the sample cell were sample gas absorbs certain wavelengths of the IR radiation. The transmitted IR radiation is detected and digitized to obtain the resulting spectrum.

The main characteristics of the equipment are:

- Scan frequency: 0.1 spectra/s
- Resolution: 3.86 cm^{-1}
- Wave number range: 700 – 4200 cm^{-1} with ZnSe/DTGS
- Volume of gas cell: 0.22 l
- Sampling flow rate: 4 l/s

The FTIR is coupled to the exhaust duct of the cone calorimeter in the same position at which it performs its measurements to ensure uniformity of the results. Gas is transported at 180 ºC from the sampling point to the spectrometer and was not dried before passing through the FTIR gas analyzer. This avoids water condensation and the trapping of water soluble compounds as well as the quantification of water vapour.

Additionally, the temperature at the exposed face was measured. A K-Type thermocouple was placed at the surface of the sample exposed to cone radiation. Thermocouples can operate up to 1200 ºC and have an error of ±2.5 ºC in the temperature range from 0 to 333ºC and an error of 0.0075 * T for temperatures above 333 ºC, where T is the temperature in Celsius.

3. Materials and Methods

The materials used in the study are two different pavements (concrete pavement and asphalt pavement) used frequently in tunnel construction. Pavement A corresponds to a concrete pavement (HF-4.5 MPa) produced according to the dosage shown in Table 1. The water cement ratio used is 0.47 and four different aggregate fractions was employed (two fine aggregate fractions and two coarse aggregate fractions).

Track samples were produced and then were cut and shaped to meet the required dimension for testing (area of 100 mm x 100 mm and 50 mm height). Given the nature of the manufacturing and subsequent cutting process, the samples presented a variable mass in the range of 1137 – 1177 grams, with an average mass of 1159.2 grams.

Table 1.Mix proportion of concrete pavement

Compound	Characteristics	Dosage
Cement	CEM II/A-V 42.5 R	350 kg
Fine Aggregate (crushed - calcareous)	0/4 mm	423 kg
Fine Aggregate (siliceous)	0/3 mm	227 kg
Coarse Aggregate	4/11 mm	400 kg
Coarse Aggregate	11/22 mm	900 kg
Water	-	165 L
Plasticizer	Lignosulphonate	1 L
Super- Plasticizer	Naphthalene	2 L

Pavement B correspond to an asphalt pavement (BBTM 11A (F-10), produced according to UNE-EN 13108-2 [20] and UNE-EN 13108-21[21]. A granulometric fraction of 0/16 was employed. The asphalt binder used in the manufacture of the pavement is the 45/80-65 (BM-3C), in a proportion of 4.85 %, while the manufacturing temperature of the pavement was 165 ºC. Table 2 shows the characteristics of the pavement.

Table 2.Characteristics of asphalt pavement

Characteristics	Value
% bitumen/mix	4.85
Bitumen specific weight	1.02
Bitumen volume (%)	4.73
Aggregate volume (%)	33.73
Aggregate specific weight	2.82
Relative density	2.48
Voids %	6.94

Tracks samples were produced and then were cut and shaped to meet the required dimensions for testing. Samples presented a variable mass in the range of 1269 – 1292 grams, with an average mass of 1278.9 grams.

Samples were keep in a climatic chamber until constant mass at 23 ºC ± 2ºC and 50 % ±2 % of relative humidity until constant mass. Both pavements were analyzed using a single heat flux of 75 kW/m^2. This flux is high enough to guarantee the ignition of asphalt pavement easily and it is lower than the resulting radiant heat flux incident on the pavement surface during tunnel fires [7], [22], [23].

The experiments were carried out according to ISO 5660-1[17] in a cone calorimeter made by Fire Testing Technology Limited under fully ventilation condition. Tests were carried out with a piloted ignition in air and were repeated three times for each pavement. The experiments were stopped manually if no ignition occurred after 30 minutes (concrete pavement) or 32 minutes after ignition (asphalt pavement). During the experiments, the air flow inside the exhaust duct of cone calorimeter was taken equal to 24 l/s ± 2 l/s. The analyses were focused on the following parameters:

- Heat release rate (kW/m^2)
- Ignition Temperature (ºC)
- Rate of smoke release ($(m^2/s)/m^2$)
- Analysis of gas species
- Thermal degradation

The temperature over the exposed face of the samples was recorded using a data acquisition system Agilent 34980A with a scanning frequency of 1 second. All analysis were performed simultaneously.

3.1. Gas calibration

FTIR equipment was calibrated by using concentration certified sample gases provided by Air Liquid, concretely CO and SO_2 at 17.40 ± 0.35 ppm and 825 ± 17 ppm respectively. The second one is recommended by manufacturer to ensure the proper function of apparatus. The work was designed to be focused on CO released by asphalts, and for that we calibrate the CO at low yields with certified low yield CO gas. The calibration take place once zeroing (Nitrogen 99.9% certified) was performed for each point of calibration. Six calibration procedures were repeated obtaining an average of 18.16 ± 0.14 ppm. We can conclude that CO yield results at lower CO concentrations had a relative average error of 4.4%.

4. Results and Discussion

4.1. Heat Release Rate, Temperatures and Smoke Release Rate Analysis

Fig. 1 show the heat release rate curves reported for both types of pavements analyzed during the first 1800 seconds of the tests. As it is show in the figure, none of the concrete pavement samples ignite at tested temperatures so that its contribution to fire growth is null. By contrast, all the samples of bituminous pavement ignite between 65 and 100 seconds after the start of the tests, contributing to the fire with a heat release rate up to 81.9 kW/m^2.

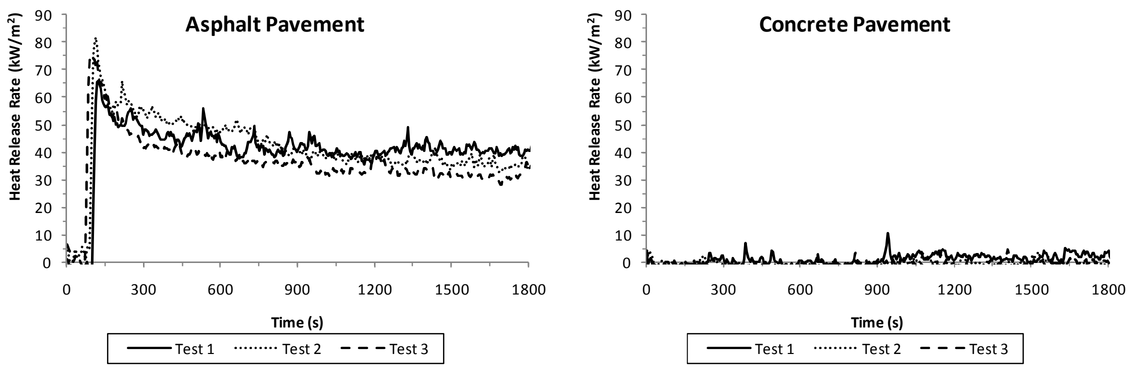

Fig. 1. Heat release rate of both pavements during tests

Fig. 2 shows the temperatures reported by the thermocouple over the exposed face of the samples. As it is shown in the figure, temperatures in the exposed face increase similarly for both concrete and asphalt pavement until ignition of asphalt pavement is produced. After ignition, a sharp increase in the temperatures over the exposed face was reported in asphalt pavement. Table 3 shows the ignition temperatures ranges calculated for both materials.

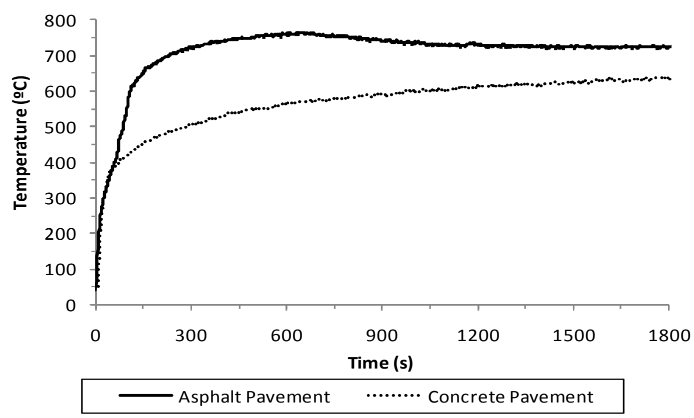

Fig. 2. Temperatures reported over the exposed face of both pavements during tests

Table 3.Ignition temperature range for both materials

Material	**Ignition Temperature (ºC)**
Concrete Pavement	> 651
Asphalt Pavement	430 – 440

Fig. 3 shows the rate of smoke release for both pavements during tests. As is shown in the figure, the maximum rate of smoke release rate of the asphalt pavement (2.18 (m^2/s)/m^2) is produced after the ignition and it is 7.3 times the maximum smoke release rate reported for concrete pavement (0.30 (m^2/s)/m^2). The average smoke release rate for asphalt pavement (0.21 (m^2/s)/m^2 is 21 times the average smoke release rate for concrete pavement (0.01 (m^2/s)/m^2). However, it is necessary to clarify that in the case of concrete pavement these fumes are mainly composed by water vapour.

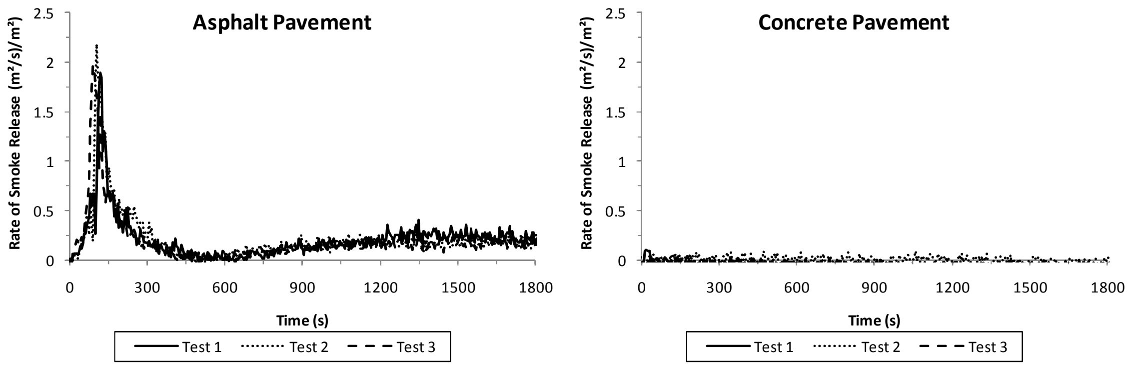

Fig. 3. Rate of smoke release of both pavements during tests

The opacity of the fumes generated was significantly different for both pavements. The average extinction coefficient measured inside the exhaust duct was 0.07 m^{-1} in the case of asphalt pavement and 0.01 m^{-1} in the case of concrete pavement. However, the maximum values reported in the case of the asphalt pavement were considerably high (0.73 m^{-1}) in comparison with the maximum values reported for concrete pavement (0.10 m^{-1}).

4.2. Analysis of Gas Species

During the tests, only few species of the total analyzed reported significant concentrations. The following provides a detailed description of the emissions of these gases during the experiments.

Fig. 4. shows the water vapour concentration measured for both pavements during the tests. As shown in the figure, after the ignition of asphalt pavement a slight increase in the water vapour concentration is reported. This increase can be associated to complete combustion phenomena.

On the other hand, concrete pavement reported a very slight increase of water vapour concentration. The maximum values were reported at the same time than the maximum mass loss rate. This result was expected, because the mass loss that occurs in concrete within the temperature range analyzed is associated to the evaporation of water present inside concrete (concrete drying).

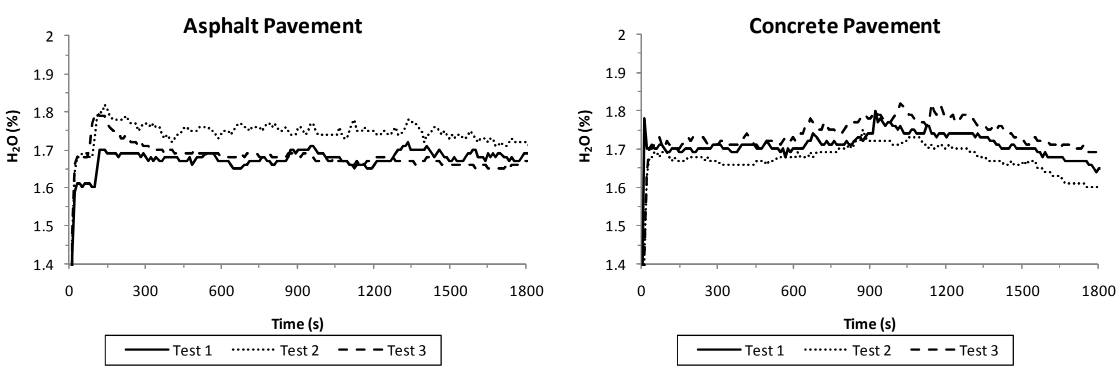

Fig. 4. Water vapor concentrations measured for both pavements during tests

Fig. 5 shows the concentration of carbon dioxide (CO_2) obtained during the tests for both materials. As is shown in the figure, after the ignition of the asphalt pavement a sharp increase of the concentration of CO_2 is produced. This increase is associated to the combustion process of the bitumen and generates significant amounts of CO_2, while in the case of concrete pavements, the level remain low and constant throughout the tests.

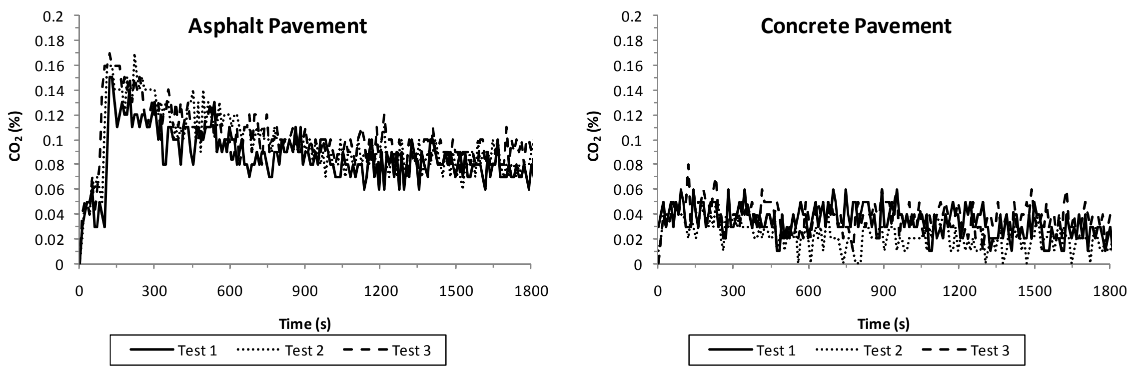

Fig. 5. CO_2 concentrations measured for both pavements during tests

Fig. 6 shows the concentration levels of carbon monoxide (CO) measured during tests for both materials. As is shown in the figure, after the ignition of bituminous pavement the concentration of CO increases up to 15 ppm. CO is a very volatile and flammable gas and part of the released CO serves to keep the flame over the surface of the material. However, once the sample surface is calcined, flames were only observed near the edges of the samples and all the CO released do not reacts.

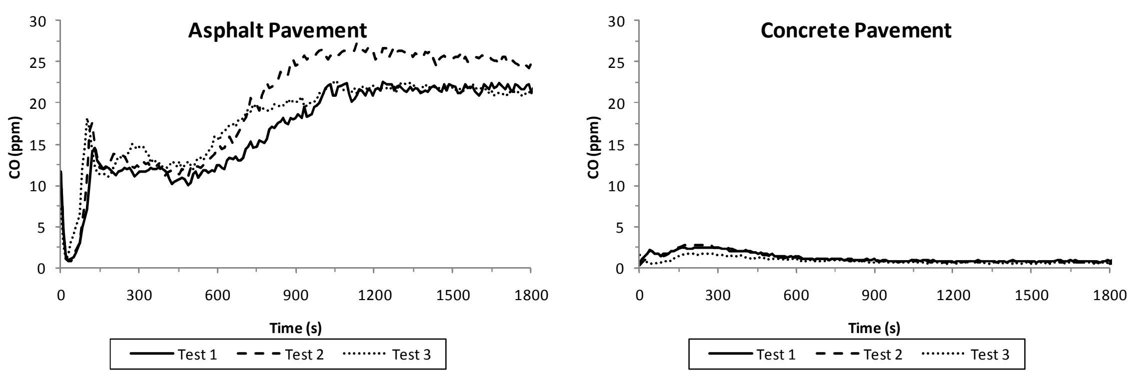

Fig. 6. CO concentrations measured for both pavements during tests

Bitumen, very rich in hydrocarbons, oxidizes very quickly to CO around 440 ºC, and subsequently, the CO is oxidized to CO_2, according to the following scheme:

$$\mathrm{HC} + \mathrm{xO_2} \xrightarrow{\text{yields}} \mathrm{yCO} + \mathrm{zH_2O} \quad (1)$$

$$\mathrm{CO} + \frac{1}{2}\mathrm{O_2} \xrightarrow{\text{yields}} \mathrm{CO_2} \quad (2)$$

The first of this process is very fast while the second is relatively slow. If the porosity of the pavement allows the contact of the bitumen and the oxidant at a temperature high enough to overcome the activation energy of the first reaction then CO_2 is produced [10], [24], but if there is not enough oxidant, the second reaction will not take place, leading to a net release of CO.

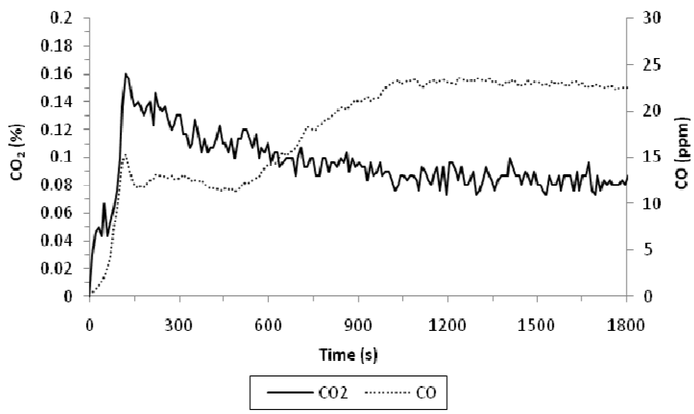

Fig. 7. Average production of CO_2 versus the average production of CO for bituminous pavement

Fig. 7 shows the average production of CO_2 and CO versus time for asphalt pavement. As is shown in the figure, there is a slight delay (5 seconds) in the time were the peak value of CO_2 is reported in comparison with the peak value of CO. As the test runs the levels of CO emissions increases and decreases the levels of CO_2, which indicates incomplete combustion.

Fig. 8. shows the concentrations of sulphur dioxide (SO_2) detected in the test for both materials. This gas is specially irritant and toxic and affects the respiratory tract, especially the mucosities and lungs. In contact with moisture the sulphur dioxide is converted into sulphuric acid, which is highly corrosive and damaging to health. The levels of SO_2 detected in the tests to asphalt pavement were especially high with a peak value of 17.94 ppm just after the ignition and a mean value of 5.37 ppm during the first 1800 seconds.

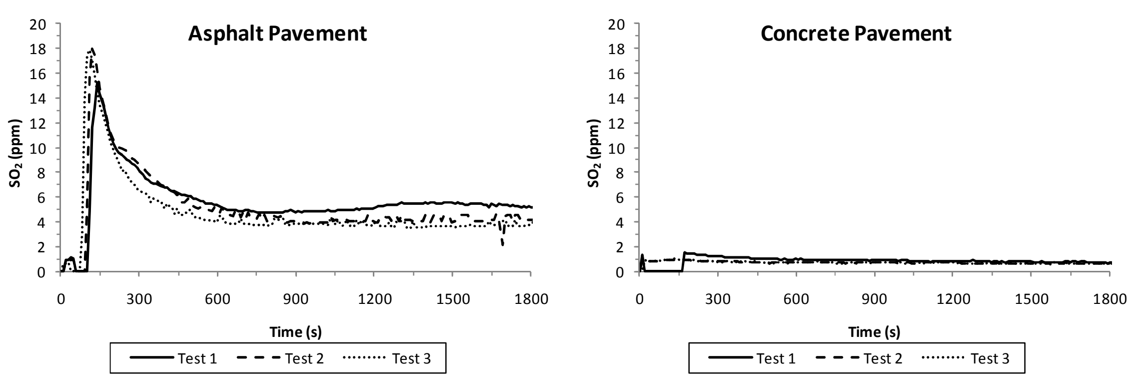

Fig. 8. Production of SO_2 measured for both pavements during tests

The gas concentrations quantified during the experiments have been obtained from measurements made in the exhaust duct of cone calorimeter. However, this result must be extrapolated to be used in full-scale scenarios [25].

The mass emitted of each compound have been calculated as the mass fraction released of each gas species multiplied by the mass loss reported in the test in the time interval that is being analyzed.

$$m_\alpha(g) \ = M_\alpha(\%) \times ML(g) \tag{3}$$

Where: m_α is the mass of the α specie, M_α is the mass fraction of the compound (in percent) and ML is the mass loss (in grams) reported in the test.

The mass fraction of each gas species released during test depends of the volume fraction and the molar mass of each component:

$$M_\alpha(\%) \ = \frac{V_\alpha(\%)}{\sum(V_\alpha(\%) \times M_\alpha)} M_\alpha \tag{4}$$

Where: M_α is the mass fraction of the specie analyzed (in percent), V_α is the volume fraction of the compound (in percent) and M_α is the molar mass of the compound.

Table 4 shows the average concentration and the average mass of the main gas species emitted during the tests (1800 seconds) for each material. As is shown in the table, except for H_2O, the concentrations obtained in the tests over the asphalt pavements are higher than concentrations reported for concrete pavement. In the case of asphalt pavement the emission of H_2O can be associated to the combustion process, while in the case of concrete pavement the release of water vapor release can be associated to drying at high temperatures. In fact, H_2O represents nearly 98% of the total mass loss reported in the tests.

Table 4.Average concentration and mass released during test for both pavements

Gas Specie	Asphalt Pavement		Concrete Pavement	
	Average Concentration (ppm)	Mass Released (grams)	Average Concentration (ppm)	Mass Released (grams)
H_2O	1391.90	12.47	1530.98	28.03
CO_2	447.51	8.09	23.33	1.04
CO	19.20	0.23	1.07	0.03
SO_2	5.37	0.14	0.77	0.05

The concentrations reported for the rest of gases analyzed (N_2O, NO, NO_2, NH_3, HCl, HF, C_2H_6, C_2H_4, C_3H_8, C_6H_{14}, CH_2O, HCN, HBr, C_3H_4O and C_6H_6O) were, in all cases, lower than 3ppm both for asphalt and concrete pavements.

4.3. Thermal Degradation

Fig. 9 shows images of asphalt pavement before and after carrying out the tests. As is shown in the figure, all the surface of the asphalt pavement was calcined during the burn out of the pavement, penetrating up to 24 mm into the sample. There was reported a severe material degradation, detachment of part of the aggregates as the asphalt binder is consumed by the flames.

Fig. 9. Asphalt pavement sample before and after the tests

In the case of concrete pavements (Fig. 10), some minor thermal cracks were reported over the surface as well as the lateral faces of the sample. However, sample integrity is maintained after the test. Also, a slight change on the surface coloration was observed. This phenomenon can be associated to physical-chemical changes in concrete microstructure at high temperature, as the decomposition of the calcium hydroxide in calcium oxide and water at high temperature.

Fig. 10. Concrete pavement sample before and after the tests

5. Conclusions

In the present study we have presented the experimental results of the analysis of two frequently used pavement types in road tunnel construction. The analysis were focused to those aspects that allowed to assess the contribution of each pavement to fire growth, the evaluation of the gases emitted and quantification of the physical degradation of both pavements due to thermal attack. The experiments were carried out using a cone calorimeter coupled with an FTIR to simultaneously evaluate the heat release rate and gas species emitted. The results have allowed analyzing the fire behaviour of both pavements, not only from the standpoint of their contribution to fire growth, in terms of the heat release rate, but also from the point of view of the toxic gases generated during combustion. This aspect acquires special significance in severe confined fires as in the case of tunnel fires.

In terms of the contribution of pavements to fire growth, has been proved that the contribution of concrete pavement is null, since no one of the three samples analyzed ignites at the selected heat flux, even when surface temperatures exceeded 650 ºC. In the case of asphalt pavement, was reported the ignition in all the tests carried out, within a temperature range from 430 to 440 ºC and very low times (less than 100 second). Once the ignition occurs, pavement combustion contributes with an average heat release rate of 39.4 kW/m^2 in 30 minutes and a heat release rate peak of 81.9 kW/m^2.

In terms of the fumes produced and visibility levels has been shown that concrete samples produces very little smoke during test (almost 98 % percent of mass loss was water in the form of water vapor) with a very low opacity. In the case of asphalt pavements, very opaque fumes were reported. Also, the rate of smoke release of these fumes was 21 times higher than in the case of concrete pavement. Visibility levels detected inside the exhaust duct also differ considerably between concrete and asphalt pavements. The extinction coefficient reported for asphalt pavement was 7 times the extinction coefficient measured for concrete pavement, both maximum and average values.

In terms of gas production, during the combustion of the asphalt pavement significant concentrations of various gases are produced. These concentrations can even exceed the maximum levels allowed by the Occupational Exposure Limits to Chemical Agents in Spain 2011[26], as for example, in the case of SO_2. The levels of water vapour detected in concrete pavement tests were slightly higher than in the case of asphalt pavement. However, in the case of concrete pavement the water production is associated with drying processes at high temperatures, while in the case of asphalt pavement is a combustion product.

No spalling or detachment was observed during the tests on concrete pavements, although some minor cracks were reported over the exposed surface as well as colour changes. In the case of asphalt pavement a severe degradation of the material was observed, including the calcinations of an important layer (around 2 cm) of the material and the detachment of aggregates.

In general, the results have shown that the overall fire behaviour of concrete pavement is better than the asphalt pavement. However, it is important to denote that the study was limited only to two pavements types. In that sense, and extrapolation or generalization of these results to other pavement types or conditions could be very risky without prior analysis.

Acknowledgments

This work has been developed based on the Agreement between the Spanish Institute of Cement and its Applications (IECA) and GIDAI Group at the University of Cantabria for the "Análisis Experimental del Comportamiento al Fuego de Pavimentos Empleados en Túneles de Carretera". The authors would like to thank the Spanish Institute of Cements and its Applications for its financial support.

References

[1] A. Noumowe, Asphalt Ignition in case of Fire in Civil-Engineering Structures: chemical analysis. 10th International Fire Science & Engineering Conference. Edinburgh, Scotland, (2004).

[2] F. Hacar Rodríguez, Estadísticas de Averías, accidentes e incendios de vehículos en túneles carreteras (2ª parte). Cimbra: Revista del Colegio de Ingenieros Técnicos de Obras Públicas 373 (2007) 30-42.

[3] Technical Note, Improving fire safety in tunnels: The concrete solution, CEMBUREAU, Brussels, 2004.

[4] A, Leitner, The fire catastrophe in the Tauern Tunnel: experience and conclusions for the Austrian guidelines. Tunneling and Underground Space Technology. 16 (2001), 217-223.

[5] R.O. Carvel, J.L. Torero, The contribution of asphalt road surface to fire risk in tunnel fires: preliminary findings. in: Proc. Int. Conf. Risk and Fire Engineering for Tunnels, Stations and Linked Underground Spaces. ISBN: 1-901808-25-4, Tunnel Management International, Hong Kong. Organized by. (2006) pp. 83-87.

[6] S. Colwell, C. Rock, Reaction to fire behaviour of pavement surfaces. in: Proceedings of the 11th International Conference on Interflam 2007. ISBN: 978-0-9541216-8-6, Interscience Communications, Greenwich, London, 2007, pp. 123-133.

[7] S. Colwell, J.C. Nicholls, J.L. Torero. Test methodologies for reaction to fire of pavement materials. Samaris Final Report SAM-04-D20, 2005

[8] T. Xu, X. Huang, Y. Zhao, Investigation into the properties of asphalt mixtures containing magnesium hydroxide flame retardant. Fire Safety Journal 46 (2011), 330-334.

[9] T. Xu, X. Huang, Study on combustion mechanism of asphalt binder by using TG-FTIR technique. Fuel 89 (2010), 2185-2190.

[10] B. Schartel, H. Bahr, U. Braun, C. Recknagel, Fire risks of burning asphalt, Fire and Materials 34 (2010) 333–340.

[11] A. Tewarson, Smoke emissions in fires, Fire Safety Science–Proceedings of the Ninth International Symposium, IAFSS, (2008). 1153-1164

[12] M. Suzanne, S. Ukleja, M. Delichatsios, J. Zhang and B. Karlsson, Fundamental flame spread and toxicity evaluation of fire retarded polymers, Fire Safety Science-Draft Proceedings of the Eleventh International Symposium, IAFSS (2014)

[13] UNE-EN 13823, Ensayos de reacción al fuego de productos de construcción. Productos de construcción, excluyendo revestimientos de suelos, expuestos al ataque térmico provocado por un único objeto ardiendo, (2012)

[14] World Road Association (PIARC), Fire and Smoke Control in Road Tunnels, PIARC Committee on Road Tunnels (C5), 1999.

[15] Capote J., Alvear D., Lazaro M. et al. Análisis del Comportamiento de Nuevas Mezclas Bituminosas ante un Incendio en un Túnel de Carretera. Internal Report, GIDAI Group, University of Cantabria (2010).

[16] EN ISO 9239-1:2010, Reaction to fire tests for floorings – Part 1: Determination of the burning behaviour using a radiant heat source. International Organization for Standardization, (2010).

[17] ISO 5660-1:2002, Reaction-to-fire tests -- Heat release, smoke production and mass loss rate -- Part 1: Heat release rate (cone calorimeter method). International Organization for Standardization, (2002).

[18] W. De Lathawer, Effects of pavement on fires in road tunnels. Routes/Roads 334 (2007) 54-61.

[19] T. Hakkarainen, E. Mikkola, J. Laperre, et al. Smoke Gas Analysis by Fourier Transform Infrared Spectroscopy - Summary of the SAFIR Project Results. Fire and Materials 24 (2000), 101-112.

[20] UNE-EN 13108-2:2007. Mezclas bituminosas. Especificaciones de materiales: Parte 2: Mezclas bituminosas para capas delgadas. Asociación Española de Normalización y Certificación AENOR, (2007).

[21] UNE-EN 13108-21:2007. Mezclas bituminosas. Especificaciones de materiales. Parte 21: Control de producción en fábrica. Asociación Española de Normalización y Certificación AENOR, (2007).
[22] H.Y. Ingason, A. Lönnemark, Heat release rate from heavy goods vehicle trailers fires in tunnels. Fire safety Journal 40 (2005), 646-668.
[23] A. Lönnemark, H.Y. Ingason, Gas temperatures in heavy goods vehicle fires in tunnels. Fire safety Journal 40 (2005), 506-527.
[24] A . Fullana, R. Font, J.A. Conesa, P. Blasco, Evolution of Products in the Combustion of Scrap Tires in a Horizontal, Laboratory Scale Reactor, Environmental Science and Technology 34 (2000), 2092–2099.
[25] J. Luche, T. Rogaume, F. Richard, E. Guillaume, Characterization of thermal properties and analysis of combustion behavior of PMMA in a cone calorimeter. Fire Safety Journal 46 (2011), 451-461.
[26] Limites de Exposición Profesional para Agentes Químicos en España 2011. Ministerio de Trabajo e Inmigración. Instituto Nacional de Seguridad e Higiene en el Trabajo, 2011.