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Study of tunnel pavements behaviour in fire by using coupled cone calorimeter – FTIR analysis

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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 °C 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.

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 [1–4]. 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 [1,5–8].

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 CO_2. 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.

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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 °C [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/min

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 °C 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 thermocouple was placed at the surface of the sample exposed to cone radiation. Thermocouples can operate up to 1200 °C and have an error of ± 2.5 °C in the temperature range from 0 to 333 °C and an error of 0.0075^*T for temperatures above 333 °C, 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 × 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 g, with an average mass of 1159.2 g.

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 °C. Table 2 shows the characteristics of the pavement.

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 g, with an average mass of 1278.9 g.

Samples were keep in a climatic chamber until constant mass at 23 ± 2 °C 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 min (concrete pavement) or 32 min after ignition (asphalt pavement). During the experiments, the air flow inside the exhaust duct of cone calorimeter was taken equal to 24 ± 2 l/s. The analyses were focused on the following parameters: