Asphalt mixture fire performance at full scale. PAVIREX project

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ABSTRACT

Most roads and tunnels in Europe use asphalt mixtures as upper layer due to their excellent properties, but the fire performance of these materials has been always a subject of discussion.
In this paper the study of the fire performance of different asphalt mixes (conventional and modified with different aditives) is reported.
The study was carried out at laboratory and full scale. Asphalt mixtures were evaluated at laboratory level using two different tests: The cone calorimeter test, as described in the ISO 5660, and a new test developed to study fire propagation in asphalt mixtures slabs. Then, the best rated modified mixture and the conventional one were tested at full scale using different fire loads in the San Pedro de Anes test tunnel (Asturias, Spain).
The main conclusion obtained from the different tests carried out during this four years project is that there is no fire propagation over asphalt mixtures, but a surface degradation in those zones were, due to an external heat source (> 400 ºC), asphalt burns.
Results showed in this paper have been obtained in the development of the PAVIREX project, granted by the Spanish "Ministerio de Economía y Competitividad", call "Innpacto 2011".

Keywords: Asphalt, Fumes, Safety

1. INTRODUCTION

The negative impact that accidents have in society is a serious concern due to their human, social and economic consequences. In tunnels, safety is usually associated to subjects like ventilation, lighting, communication and evacuation systems. However, the use of pavements to improve safety in case of fire scenarios triggered as a result of accidents inside the tunnel is a line of research that has not been significantly developed until recently. A properly design of the pavement can help minimise the consequences of incidents such as fire and the toxicity of fumes [1, 2, 3]. The same concern can be transferred to other facilities with similar characteristics to the tunnels, such as industrial buildings with high theoretical fire load or the paving of underground car parks covered under the European standard EN 13501-1. [4]

Two specific aspects have been studied in depth in the PAVIREX project:

- Studying the fire behavior of conventional asphalt mixes and checking its suitability as surface layers in tunnels.
- Improving the fire behavior of asphalt mixtures using various flame retardant additives

To improve the fire behavior of asphalt mixtures different types of retardants such as aluminum and magnesium hydroxides, polyphosphoric acid or various phosphates and polyphosphates have been used, in the mixture or as a binder modifier.

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The fire reaction studies have been conducted on two different levels:

- Laboratory scale, split in two according to the size of the sample:
    - Small scale, using the cone calorimeter equipment on test specimens measuring 100 mm x100 mm x10 mm (w x l x h).
    - Medium scale, using a test designed specifically for this study, in order to check the possible flame spreading in these materials, consisting in applying a direct flame on specimens of asphalt mix of size 410mm x 260 mm x 50 mm (w x l x h).
- Full scale, in a tunnel specially designed to perform this type of testing in a controlled way, testing both conventional and improved bituminous mixtures with different fire loads, including a burning car.

A significant amount of work was carried out in the PAVIREX project but this paper focuses only on the reaction to fire.

2. FIRE REACTION STUDY OF THE BITUMINOUS MIXTURES DESIGNED AT LABORATORY SCALE

After an initial pre-study, a phophinate was selected as a flame retardant additive, and has been used in different quantities (0.7%, 1.0% and 1.4%, in weight) on the bituminous mixture, replacing filler. The full study has been carried out on an asphalt concrete AC16 surf 50/70 S as described in EN 13108-1 [5], using silica aggregates.

2.1 Small scale study. Cone calorimetry test.

As stated previously, small scale fire reaction tests of the bituminous mixtures developed along the project were carried out on Fire Testing Technology (FTT) cone calorimeter equipment according to the ISO 5660 standard under fully ventilated conditions. [6] This name was derived from the shape of the truncated conical heater used to irradiate the test specimen with fluxes up to 100 kW/m^2.

Different fire properties of the mastics were evaluated, such as heat release rate (HRR, kW/m^2), peak of heat release rate (pHRR, kW/m^2), time to ignition (TTI, seconds), total heat released (THR, MJ/m^2), mass loss rate (MLR, g/(s x m^2)), peak of mass loss rate (pMLR), Maximum Average of Heat Emission (MARHE, kW/m^2) and specific extinction (SEA, m^2/kg), reflecting the smoke production. The measuring principle is that of oxygen consumption in the combustion gases of a specimen subjected to a defined heat flux. The produced gases are collected in an exhaust duct system with centrifugal fan and a hood and the HRR is calculated, based on the fact that there is a constant relationship between the mass of oxygen consumed from the air and the amount of heat released throughout product combustion. A schematic representation of this equipment is shown in Figure 1.

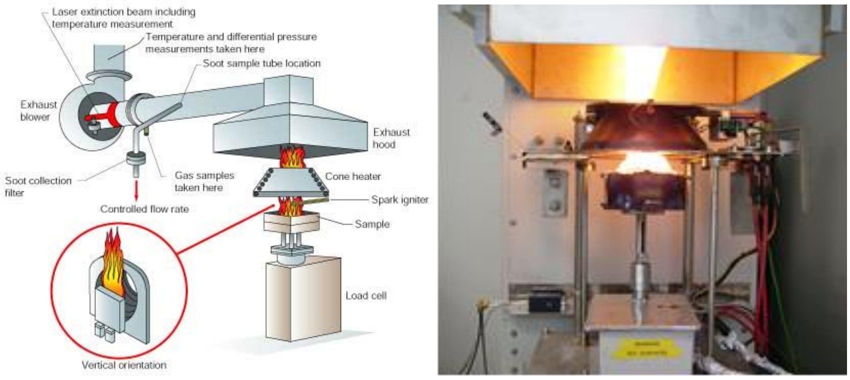

Figure 1: Schematic representation of the cone calorimeter.

Specimens of size 100 mm x100 mm x10 mm (w x l x h) were tested in the horizontal position using the retainer frame wrapped in aluminum foil and placed at a distance of 25 mm from the cone base and considering a 88.4 cm^2 area. Samples have been conditioned to constant weight at a temperature of 23 $\pm$ 2 ºC and humidity of 50 $\pm$ 5 % before testing, according to the ISO 554 standard. [7]

All the tests were performed at least in triplicate and the average values are reported herein. External heat flux was set at 40 kW m^{-2}, and lead to reasonable burning time.

The most effective flame retardant dosages are 1 % (green) and 1.4% (blue) as can be shown in the curves of Figure 2, where the evolution of the heat release rate (HRR) with time is plotted. In the first case, the maximum value of the HRR (HRRpeak, 53.9 kW/m^2) is the lowest of all the evaluated formulations, although the ignition time takes place before (283 seconds). In the second case, even if the maximum of the HRR is higher than in the previous one (HRRpeak, 76.59 kW/m^2), ignition takes place later (378 seconds). The delay in the ignition time can be beneficial for the large scale test, so the 1.0 and 1.4% phosphinates dosages have been the ones chosen for the large scale test.

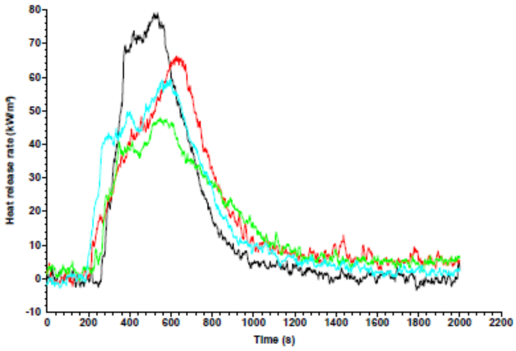

Figure 2: Heat release rate curves of the reference material (black) and the specimens with different flame retardant dosage: 1.4% (blue), 1% (green) and 0.7% (red).

2.2 Evaluation of the bituminous mixture smoke: toxicity and opacity

The same formulations have been evaluated in the smoke density chamber following the ISO 5659-2 standard and using specimens of size 75 mm x75 mm x16 mm (w x l x h). Specimens were tested at a flux of 50 kW/m^2 without a pilot flame, being these conditions similar to the ones that the bituminous mixtures are going to suffer in the large scale test.

The most important parameters obtained from this test are: specific optical density at minute four of the test ($Ds_{(4min)}$), cumulative value of specific optical densities in the first 4 minutes of the test (VOF4, min) and the maximum optical density in the test chamber (Ds_{max})

Taking into account the obtained results (Table 1), we can say that when a flame retardant is added to the formulation, an impartial combustion takes place generating more dark fumes during the first four minutes of the tests (higher VOF_4 and $Ds_{\mathbf{(4min)}}$ values). However, in all these cases when a flame retardant is added, the maximum value of the specific density (Ds_{max}) is lower or is reached at higher times than the values obtained without flame retardants. At times higher than 4 minutes, the Ds reached values are always lower when a flame retardant is added (Figure 3).

Table 1: Smoke density chamber results related to opacity.

Flame retardant Content (%)	t_{ig} (s)	t_{fo} (s)	$Ds_{(4min)}$ (dimensionless)	Ds_{max} (dimensionless)	Time to $Ds_{max.}$ (s)	VOF_4 (min)
0.0	-	-	29.1	608.0	797	28.3
0.7	389	END	41.5	343.5	780	44.9
1.0	-	-	45.1	619.8	1200	41.4
1.4	not registered	END	45.0	410.7	914	46.5

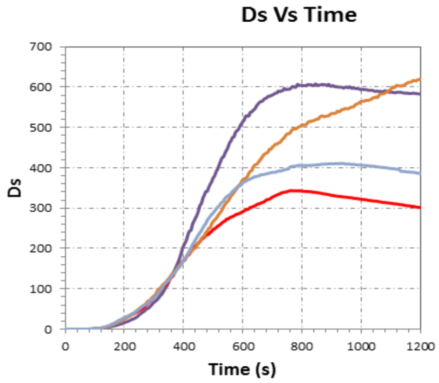

Figure 3: Ds-time curves evolution of the reference material (purple) and the specimens with different flame retardant dosage: 1.4% (blue), 1% (orange) and 0.7% (red).

In order to determine the nature of the gases produced during the combustion of the four bituminous mixtures, a Fourier Transform InfraRed equipment (FTIR) has been coupled to the smoke density chamber. Samples from the smoke density chamber have been taken at different test times (4, 8 and 20 minutes). Specimens have been tested at a 50 kW/m^2 flux with and without pilot flame. Figure 4 shows the Conventional Toxicity Index value (CITg, dimensionless). This index is function of each gas concentration within the chamber and the reference concentration for this gas, referred as Ci (limit for the people exposed to the gaseous components). Eight different gases are detected in this test (CO_2, CO, HBr, HCl, HCN, HF, NO_2 y SO_2), and is considered dangerous when the CITg value is equal to 1.

$$CIT_G = 0{,}0805 \times \sum_{i=1}^{i=8} \frac{c_i}{C_i}$$

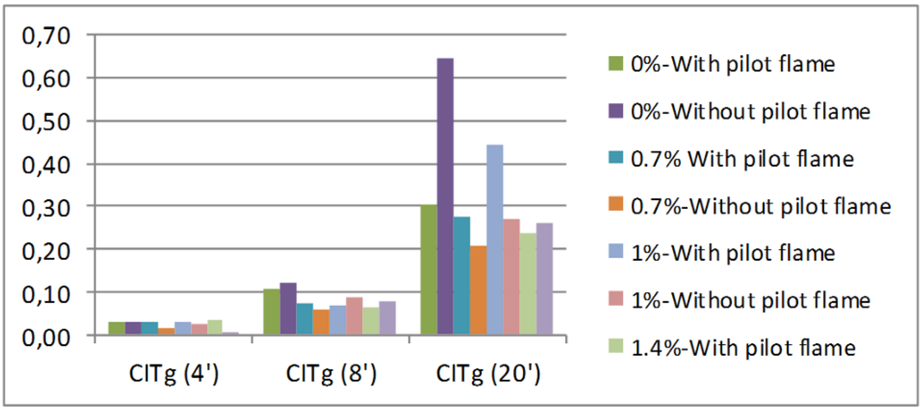

Figure 4: CITg values obtained during combustion process.

Taking into account the results obtained we can say that although none of the formulations reaches a CITg value equal to one (indicating danger), the reference formulation (without flame retardant) and the one with a flame retardant dosage of 1% (tested with pilot flame) are those that have underperformed in long test times (20 minutes). Slightly differences are shown between the formulations at short test times.

3.3 Medium scale Study. Own creation test

A simple and cheap test was developed with the aim of simulating what it would be made after in real-size samples. Larger samples were used to see if the spread of the fire exists or not along the surface. Also, different fire loads are applying directly above the bituminous mixture through a gas welding torch using butane gas (direct flame in contact with the bituminous mixture). Continuous temperature measures were registered with type K temperature sensors in all tests.

After several variations to the test a working methodology was established to provide the most suitable test procedure to enable results to be extrapolated for large scale fires.

- The size of the bituminous mixture samples is 410 mm x 260 mm and 500 mm thick.
- 114 mg/s butane gas flow because the fire power, 0.8 MW/m2, was determined from tests using standard firebrick samples.
- Distribution of the temperature sensors along the surface and the depth (at 2.5 cm and 5 cm deep) of the sample (Figure 6).
- The placement of a load of 50 kPa close to the zone on fire on the top surface.

In this test the distribution of the temperature is analyzed in the surface and along the thickness of the sample as well, the heat is applied in one side through a direct flame of butane. Besides the placement of sensors to register the temperature, 50 kPa weight is set close to the heat source that simulates the existing loads above the bituminous mixture.

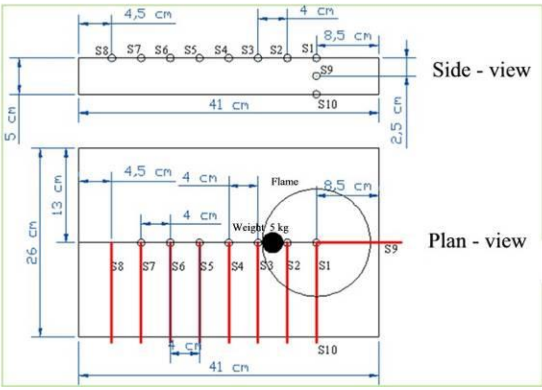

Figure 5: Distribution of sensors along the surface and the depth of the sample.

Tests were executed about the three optimized formulations according to the results from the cone calorimeter, it means, above the bituminous mixture additive-free ("white") and above mixtures with 1.0% and 1.4% of retardant. Figure 6 shows the final appearance of the different samples once the test is finished. It can be seen how the additive mixtures make a bright surface layer that it is not detected in the white sample.

Figure 6: Appearance of the specimens after the test. No additive (left) 1.0 % (center) and 1.4 %(right).

Figure 7 shows the results got from the three mixtures and from the temperature sensor placed on the surface, under the flame (graphic on the left). It has been seen that the highest temperatures in the sample are reached for the additivated mixes (close to 700ºC) while the temperature in the "white" sample is lower (around 635ºC maximum).

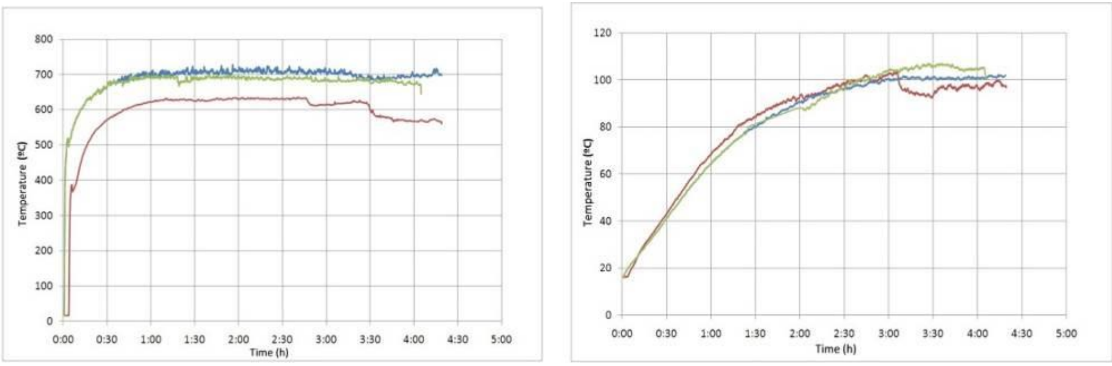

Figure 7: Temperature vs time. Nearest flame sensor (left) and No. 5 sensor (right). Additive-free sample (red), additive 1.0% (blue) and additive 1.4% (green).

Figure 8 summarizes the temperature of balance reached in each sensor for the three asphaltic mixtures tested.

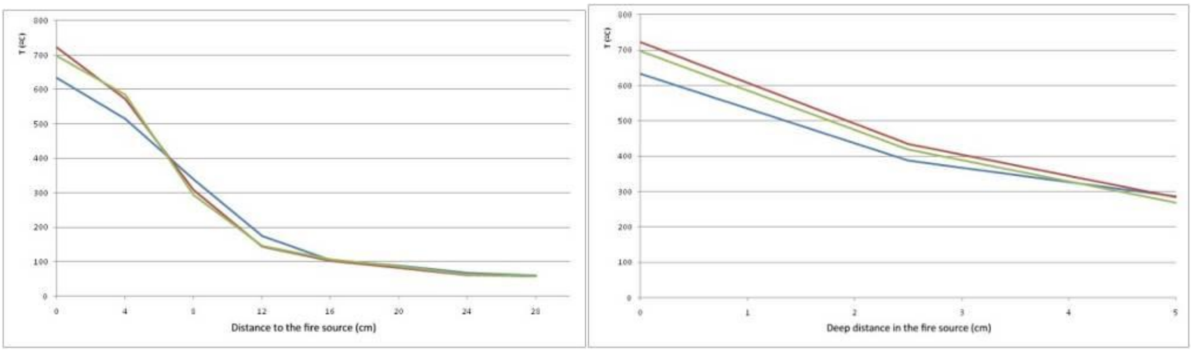

Figure 8: Balance temperatures for different sensors and samples: "White, additive-free" (blue), additive 1.0% (red) and additive 1.4% (green).

In short, it has seen that the "white" sample reaches low temperatures of balance (from 633 to 514ºC) when it is closer to the fire source than to the additive mixtures (from 722 to 573 ºC), the same occurs for the temperatures of balance reached along the thickness of the sample. This behaviour may be due to combustion of some organic components before in the "white" sample, for that, the temperature does not increase so much.

However, higher surface temperature of balance are reached in the "white" sample (340 – 104ºC), but when there is 7 cm to 16 cm from the fire source a change is produced. After this point (16 cm), the behaviour is very similar for the three mixtures (temperatures around 100ºC).

For the two mixtures with 1.0 % and 1.4% of retardant added, there are no big differences for its behaviour in the surface and in the depth. Maybe, in the last case, lower temperatures of balance are registered in the 1.4% mixture with retardant added. For the surface aspect, it has seen that the additive mixtures make a bright surface layer that it is not detected in the white sample.

3. FULL SCALE TESTS PERFORMED ON TST EXPERIMENTAL TUNNEL.

The three types of bituminous mixtures studied at laboratory scale (white, 1.0% and 1.4% retardant) were subsequently tested full scale in a specialised center (Tunnel Safety Testing).

3.1 Tunnel Facilities

The full scale test was carried out at TST facilities in the "San Pedro de Anes" Experimental Centre in the municipality of Siero, in the northern Spanish region of Asturias.

The tunnel is a 600 meters false tunnel built in concrete, with dimensions equivalent to a two lane road tunnel, and has two ventilation stations, a lower gallery for emergency and services, and three emergency exits. It has also a removable false ceiling for reproducing different ventilation conditions (Figure 9)

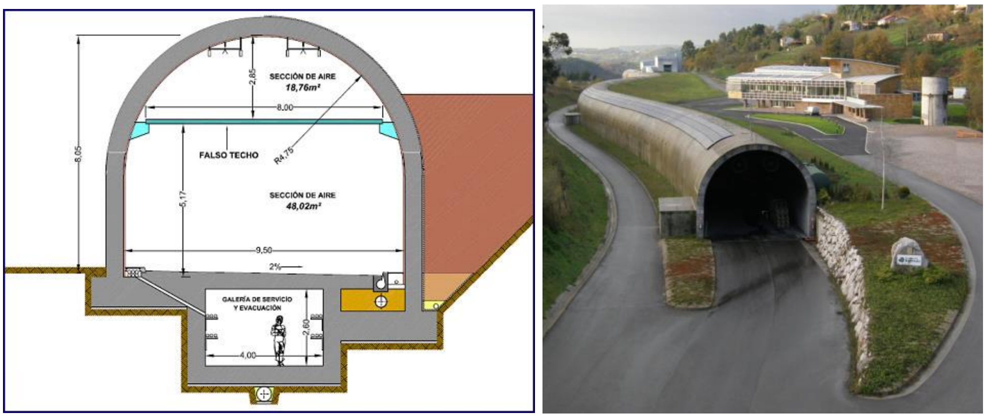

Figure 9: Cross section of test tunnel at TST.

3.2 Typology of real-scale tests

Bituminous mixtures were manufactured in the asphalt plant of Campezo Obras y Servicios SA located in Quintana del Puente (Palencia-Spain). A total of 16 plates of bituminous mixture with dimensions 120 cm x 300 cm x 5 cm (w x l x h), were spread on plates of alveolar concrete for subsequent transfer and handling in the tunnel. Two plates were used per test except for the test with the burning car where 4 plates were used.

The tests were carried out in January 2014 using different fire loads:

- Two turrets of nine dry wood pallets (0.80 m x 1.20 m) with two car tires on the right side, estimating a fire load of about 0.6 MW/m^2.
- Sixteen car and truck tires with an estimated fire load of 5-6 MW/m^2.
- A burning car with an estimated fire load of 0.5 MW/m^2 to 0.8 MW/m^2.

The air velocity in the tunnel, during the tests was 3-4 m/s equivalent to 10.8 km/h to 14.4 km/h, (critical speed). The duration of the tests was between 35-55 minutes depending on the fire load applied. The test was considered finished when self-extinction of the flame occurred or when the temperature sensor placed under the fire load or the next one, records a temperature drop under 200 ºC, proceeding to extinction.

To analyze the effect of fire on the asphalt temperature has been recorded using two different measuring systems:

- Six temperature sensors installed in the surface and at a 2.5 cm depth as described in Figure 10.
- A thermal imaging camera recording the evolution of temperatures at surface level throughout the test.

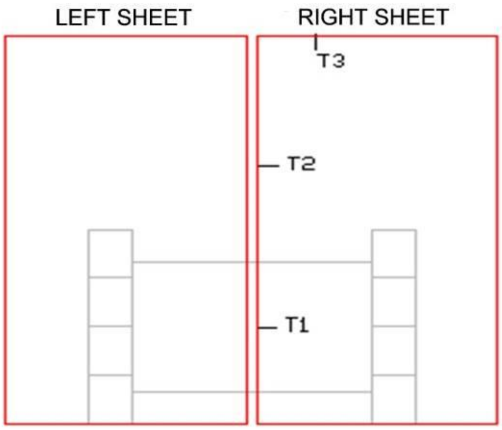

Figure 10: Temperature sensors layout.

3.3 Test results using two turrets of nine dry wood pallets as fire load.

Three bituminous mixtures with different flame retardant contents (0, 1 and 1,4 %) were tested, using an estimated fire charge of 1.2 Mw/m^2. Figure 11 shows different images of the test.

Figure 11: Images of the test.

In Figures 12a, 13a and 14a the evolution of the surface temperature during the test, measured with a thermographic camera, is displayed. Also, a photograph taken at the maximum temperature moment, registered in point A, is shown. On the other hand, Figures 12b, 13b and 14b show the results of the evolution of the surface temperature and in depth temperature, measured by the thermocouples located in the asphalt plates, as indicated in the scheme of Figure 10.

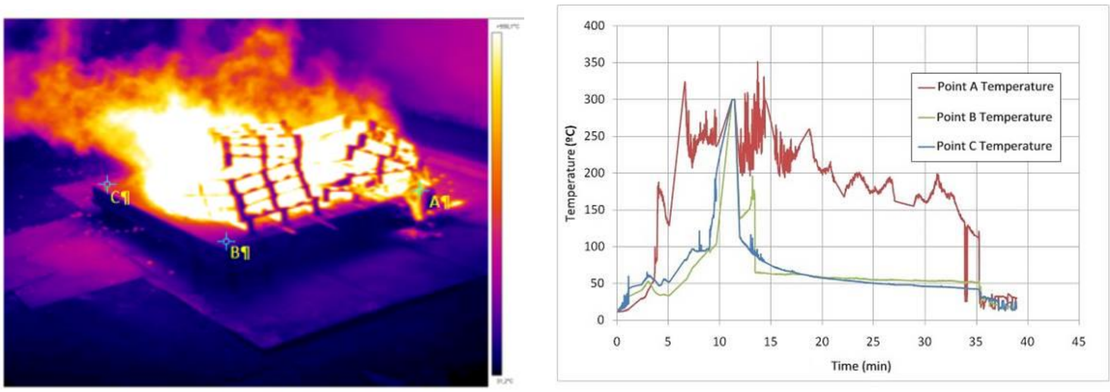

Figure 12a: Evolution of the surface temperature of the sample with no fire retardant

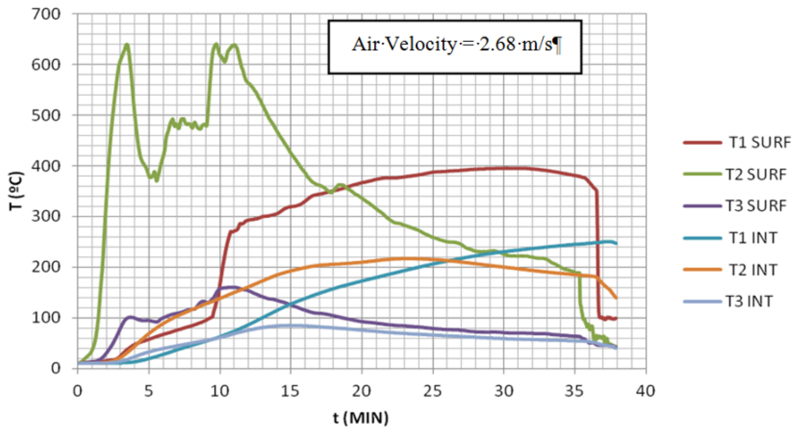

Figure 12b. Evolution of surface and in depth temperature of the sample with no fire retardant.

In this case no fire propagation in the asphalt is observed, even at the maximum temperature, T=350ºC. The highest temperature peaks are reached 5-15 minutes after ignition. It is noticed that after 10 minutes, in point C (which is located at the greatest distance from the fire charge) the temperature can reach values around 300ºC, because the flames are oriented in the direction of the tunnel air circulation, as can be seen in Figure 12a.

The analysis of the results given by the temperature sensors located in the asphalt plates indicates that no temperatures above 180ºC are reached in the surface thermocouple T3, located at the furthest distance from the fire. The thermocouple that registers the highest temperatures, close to 650ºC between 2 and 12 minutes, is the surface thermocouple T2. On the other hand, the thermocouples located inside, in the middle depth of the asphalt and in the surface coordinates of T1, T2 and T3 thermocouples, do not give temperatures above 250ºC. We remark that the thermocouple which has the same surface coordinates as T1 is just below the focus of the fire.

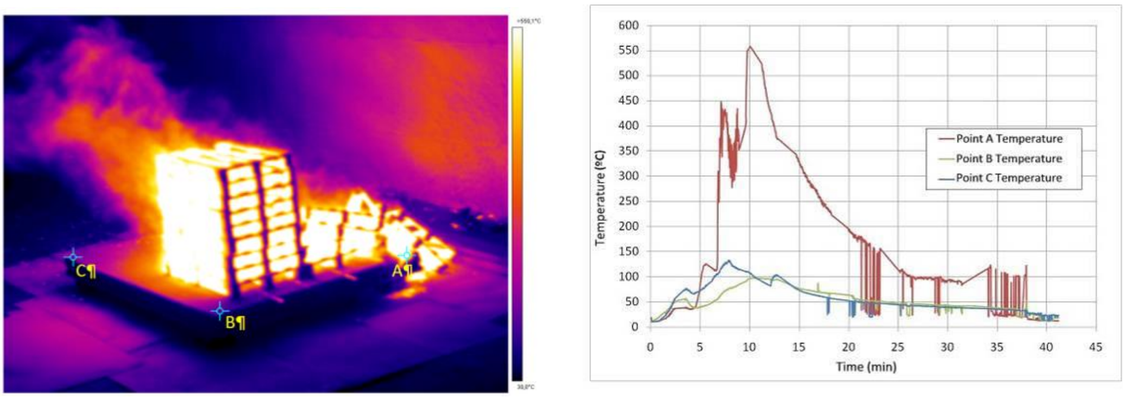

Figure 13a: Evolution of the surface temperature of sample with 1% flame retardant.

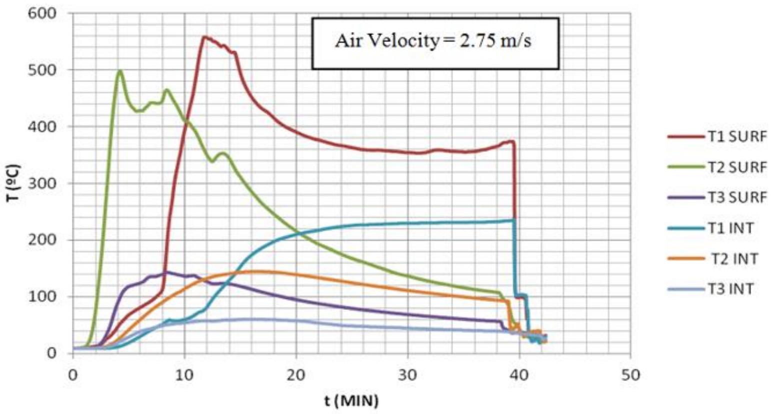

Figure 13b: Evolution of the surface temperature and in depth temperature of sample with 1% flame retardant.

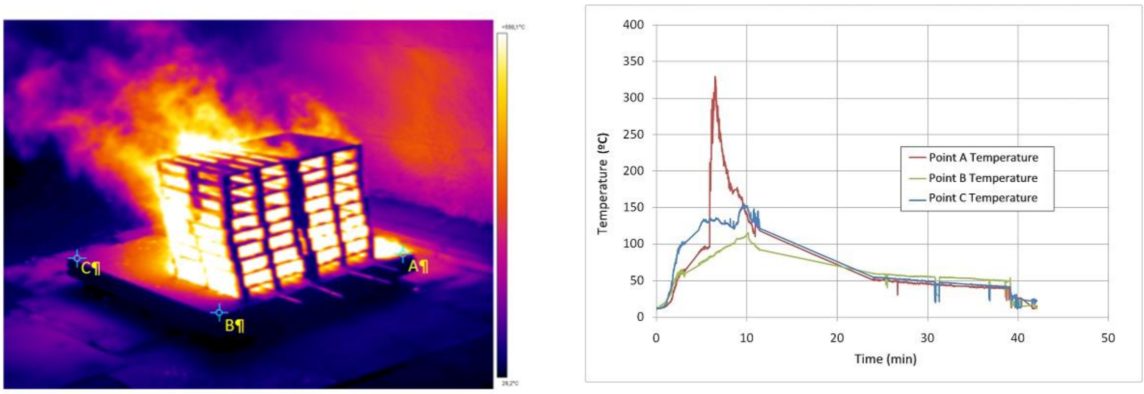

Figure 14a: Evolution of the surface temperature of sample with 1.4% flame retardant.

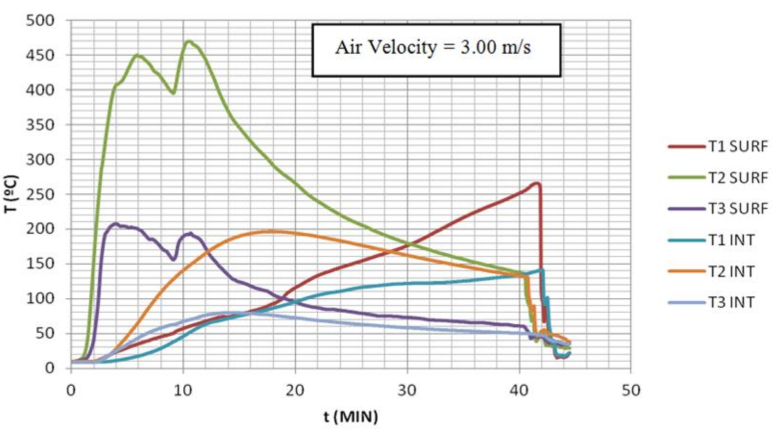

Figure 14b: Evolution of the surface temperature and in depth temperature of sample with .1.4% flame retardant.

In the case of the samples containing fire retardant, surface temperatures measured with the thermographic camera are always below 150ºC, even close to the fire focus (point B). For these samples, the observed maximum temperature is 550ºC, after 10 minutes, in particular for the case of 1% fire retardant. For the sample that contains 1.4% fire retardant the temperature grows up to 350ºC, after 6-7 minutes.

Moreover, in the case of the samples that contain fire retardant, the maximum temperature is reached close to the fire focus (point A) in the first 5-10 minutes and decreases rapidly thereafter. This temperature fall after the maximum is more evident for the sample that contains 1.4% fire retardant. However, in the sample that does not contain fire retardant, an average temperature of T=280ºC is maintained for a period of 15minutes and the decrease is more gradual.

The analysis of the sensors located in the asphalt plates reveals that higher temperatures are reached in the sample that contains 1% fire retardant: (maximum, T=550ºC in T1 after 12 minutes). For the sample that contains 1.4% fire retardant the results are: Maximum, T=470ºC in T2 after 10 minutes. On their part, the sensors located in depth indicate that no temperatures above 200ºC are reached in the sample that contains 1.4% fire retardant and not above 160 ºC in 1% sample. This demonstrates that there is a superficial damage, as can be observed in the photographs of Figure 15. In this figure, photographs of the pavement before and after the fire are shown. In the fire focus, the pavement appears superficially damaged, but the rest of the asphalt surface is in perfect shape, because fire has not been propagated across the plate.

Figure 15: Surface appearance of the bituminous mixture: Before the test (left); white sample after the test (middle); sample that containing fire retardant after the test (right).

It is difficult to reach a strait conclusion, because notwithstanding the fire charge was the same for the three samples, the behavior of the charge during the fire testing was different and, therefore, the recorded temperature varied. Nevertheless, taking into account the results of T2 thermocouple (where the highest temperatures were recorded) it could be concluded that the reached temperatures follow the sequence: white sample>1% fire retardant sample>1.4% fire retardant sample. In general these results do not agree with those obtained in the laboratory, although the results given by the calorimetric cone indicated that the better performance was reached with the sample that contains 1.4% fire retardant. Concerning the time required to reach the maximum temperature, the results of thermocouples T2 and T3 give the following sequence (from shortest to largest time): white (3 minutes) < sample with 1% fire retardant<sample with 1.4 fire retardant.

3.4 Test results using car and truck tires as fire load.

This test was carried out using three turrets made with six car tires and putting above five truck tires distributed in a symmetric way. Two plates were employed, one of concrete and other made of a bituminous mixing that contains 1% fire retardant.

Figure 16a shows the evolution of the surface temperatures, recorded with the thermographic camera, during the test. The evolution of the temperature recorded by the sensors located as shown in the scheme of Figure 10 can be seen in. Figure 16b.

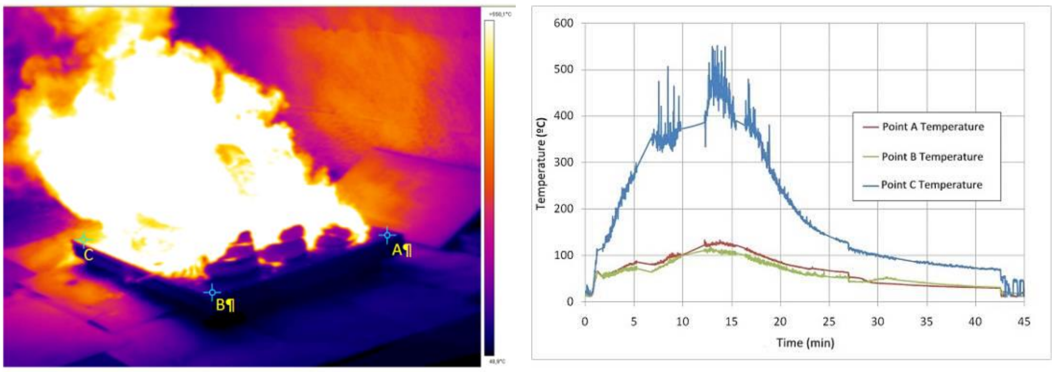

Figure 16a: Evolution of the surface temperature of sample.

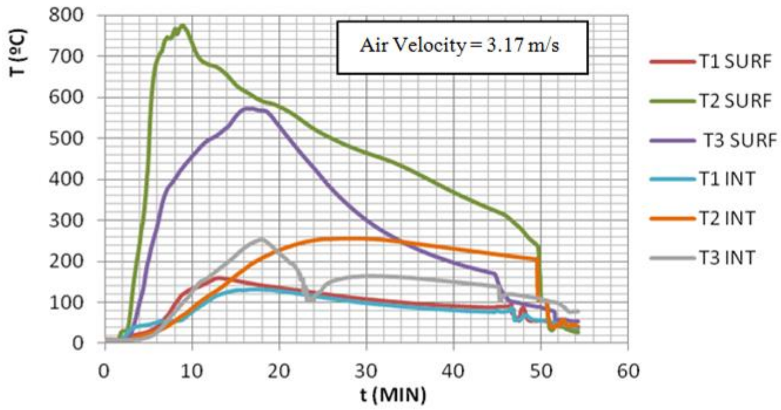

Figure 16: Evolution of the surface temperature and the in depth temperature of sample.

Figure 16a reveals that close to the fire focus temperatures barely surpass 100ºC in points B and C located in the concrete plate. However, in point A, just over asphalt mixing, surface temperatures up to 500ºC can be reached.

In Figure 16b it is observed that the maximum surface temperature registered in the asphalt is 800ºC. This is a higher temperature than that reached with the fire charge employed in the pallets turret test (550ºC), due to the more fire charge (5-6 Mw/m2 face to 1.2 Mw/m2.) employed in the tires test. As in the other cases, no flame propagation is observed and the sensors located in depth do not reach temperatures above 250ºC. Notwithstanding, a significant result was remarked during the test: Due to the internal humidity of the concrete, small concrete particles were expelled, which can lead to severe problems in fire extinction works.

In Figure 17 photographs of the appearance of the concrete and the asphalt mixing after the test are shown. Once again, it worth pointing out that the damage provoked in the asphalt is only very superficial, which is not the case of the concrete.

Figure 17: Surface appearance of the bituminous mixing plate containing flame retardant (left) and the concrete plate (right).

3.5 Test results using a car as fire load.

The last test performed consisted of burning a car placed on four plates bituminous mixture of 1.2 x 4 m with a percentage of retardant additive 1.4% each (Figure 18). In this case the fire load is estimated at 0.5-0.8 MW/m^2.

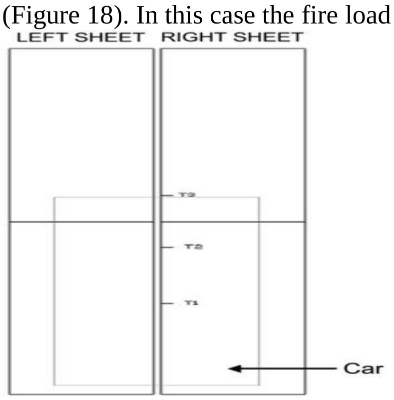

Figure 18: Scheme placing bituminous mixture plates, car and temperature sensors.

Temperature values detected by the temperature sensors placed on the plates during car burning are shown in Figure 19. The maximum temperature (close to 800 ºC) was recorded in the T3 sensor surface decreasing rapidly to 150 ºC. This was due to the fact that T3 sensor was placed near the front area of the car, whose tires start burning first and even explode. The remaining sensors evolve differently from each other as the different parts of the car were burning, but in no case temperatures as high as those detected in the T3 surf sensor were achieved.

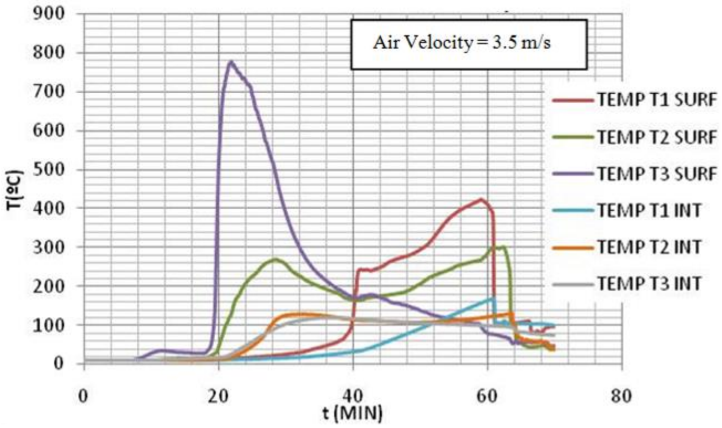

Figure 19: Evolution of the surface temperature and the in depth temperature of sample.

Regarding the temperatures recorded in the control points of the termographic image (Figure 20), low values, less than 50 ºC, were obtained but in point C, with a big peak around 18 minutes, probably due to the falling of some piece of burning material. After 35 minutes of testing, both point A and B have temperatures up to 350 ºC, while section C presents some more isolated peak with tis temperature, presumably for the same reason mentioned before.

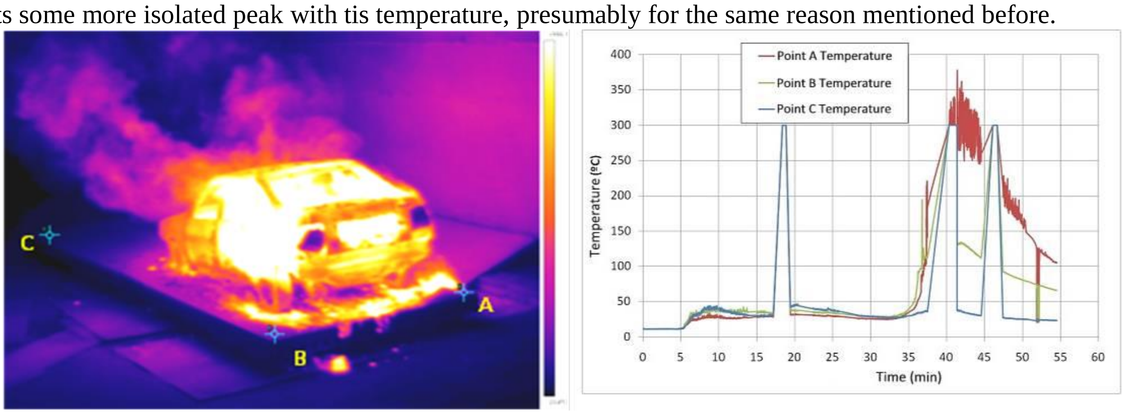

Figure 20: Evolution of the surface temperature of the bituminous mixture in the test with a burning car.

Figure 21 shows photographs of the state of the mixture right after the test is finished. As can be seen again only the surface is damaged and no collapse in the bituminous mixture due to vehicle weight is detected.

Figure 21: Bituminous mixture surface after test with a burning car.

5. CONCLUSIONS.

The main statements extracted from the exposed work regarding the fire performance behaviour of asphalt mixes are:

- In all the cases, the addition of flame retardants in the asphalt mixes decreases the heat release rate (HRR) value, being the maximum of this parameter (referenced as HRR_{peak}) displaced in the time.
- Although the conventional mixture, with no flame retardant additives, is the one that has the best behaviour during the first minutes of the test, the asphalt mixes additivated with flame retardants are the ones that present a lower value of maximum specific density (Ds_{max}).
- None of the smokes produced by the combustion of the tested formulations reaches a value of Conventional Toxicity Index (CITg) equal to one, frontier value indicating danger.
- In the case of the samples containing fire retardant, the maximum temperature is reached close to the fire focus (point A) in the first 5-10 minutes and decreases rapidly thereafter. This temperature decrease is more evident for the mixture containing 1.4% of fire retardant. However, in the sample without fire retardant, an average temperature of T=280ºC is maintained for a period of 15minutes and the decrease is more gradual.
- No fire spreading on the surface of the bituminous mixture was detected in any test, neither at laboratory level nor at full scale.

So, the use of flame retardants lead us to some advantages like a decrease in the heat released and a more rapid temperature decrease, but the main conclusion of the project is that all bituminous mixtures studied, including those with no flame retardants, are suitable for use in the paving of tunnels as neither smokes reaching the Conventional Toxicity Index, nor fire spreading was detected in any of the mixture studied.

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