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CONTRIBUTION OF CONCRETE PAVEMENTS TO THE SAFETY OF TUNNELS IN CASE OF FIRE

- SAFETY IN TUNNELS
- BEHAVIOUR OF BITUMINOUS MIXTURES AND CONCRETE IN THE CASE OF FIRE
- OTHER ADVANTAGES AND CONSTRUCTION PRACTICE OF CONCRETE PAVEMENTS IN TUNNELS

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SUMMARY

A number of tunnel fires in Europe have demonstrated the need for appropriate choice of materials for tunnel construction to ensure high safety and reliable availability to traffic. In case of fire, an incombustible and non-toxic road pavement, such as a concrete one, contributes to the safety of people (users and rescue teams) and protects both the tunnel equipment and its structure. In this document, the results of different fire tests in several countries on the behaviour of asphalt and concrete used for pavements are analyzed. It has been found that asphalt has a high calorific value, igniting rapidly after being heated and emitting toxic gases. In addition, asphalt concrete loses its mechanical characteristics (after ignition, only aggregates are still present but are no longer bound by asphalt). In comparison, concrete is incombustible, does not release fumes, does not change shape when submitted to high temperature and keeps a large part of its mechanical characteristics. Spalling phenomena are restricted to concretes that are very uncommon in pavements. Therefore it can be concluded that concrete pavements can largely contribute to the safety of tunnels in case of fire in comparison with other paving alternatives.

KEY WORDS

Fire, tunnel, pavement, concrete, bituminous mixture, safety, spalling

1. INTRODUCTION

The total length of the tunnels used for the transport of people and goods throughout Europe exceeds 15,000 km. They play an important role, even vital in some cases, in maintaining the transport infrastructure.

Road tunnels are elements in the road network which have unique characteristics, and deserve special attention. Accidents are not more frequent in tunnels than in other points of the highway itineraries, but any serious incident affecting them can cause social alarm, given the circumstances, concurrent and specific to the place where it occurs, the difficulties for rescue or evacuation, the drama caused by confinement or the serious disruption which may necessitate the temporary closure of a road, sometimes with difficult or non - existent alternatives to detour traffic.

Figure 1: Fires in St Gotthard (left) and Mont-Blanc (right) tunnels

Recent fires in European tunnels (fig. 1) have demonstrated the need to adopt some measures in order to minimise risks for both people and infrastructure, as shown in table 1 [1] [2].

Research on human behaviour under conditions of fire shows that initially most people are aware of their environment and their situation, but that the latter deteriorates within minutes due to the loss of visibility by smoke that irritates the eyes, and makes vision difficult, and also to the stress caused by heat radiated by burning elements.

Before this situation, which develops very quickly, the tunnel users react only to very strong light and sound signals. The latter is understood only with difficulty by foreign drivers, especially in tourist or border areas), but they are still obliged to make decisions within a very short period of time [3].

TABLE 1 - SUMMARY OF SOME RECENT FIRES IN EUROPEAN ROAD TUNNELS

Place of accident	Tunnel type Length	Year	Duration Temperature	Casualties	Damaged vehicles
Fréjus France–Italy	Road (1 tube) 12.9 km	2005	6 hrs 1200° C	2 deaths	9 cars
St Gotthard Switzerland	Road (1 tube) 16.3 km	2001	24 hrs 1200° C	11 deaths 35 intoxicated	10 cars 13 lorries
Gleinalm Austria	Road (1 tube) 8.3 km	2001	37 minutes	5 deaths	2 cars
Tauern Austria	Road (1 tube) 6.4 km	1999	14 hrs 1200° C	12 deaths	24 cars 16 lorries
Mont-Blanc France-Italy	Road (1 tube) 11.6 km	1999	53 hrs 1000° C	39 deaths	32 cars 2 lorries
Palermo Italy	Road	1999	–	5 deaths	19 cars 1 coach

2. BEHAVIOUR OF PAVEMENTS IN CASE OF FIRE

In view of what has been mentioned in the previous paragraphs, obviously it is necessary to ensure that all materials used in the construction of a tunnel present the highest level of safety in case of fire. In this sense, an important part of the cross section of a road tunnel is occupied by the pavement of the carriageway. The two materials that can be used in its upper layers are concrete and bituminous mixtures. However, while the first is non-combustible, the presence in the latter of bitumen, a highly flammable subproduct from oil refining, can result in significant distress in the case of a fire, increasing the fire load, emitting toxic vapours and destroying the structural properties of the material, which is partially or totally transformed into an unstable group of loose particles .

Ignition of bituminous mixtures has been observed in numerous laboratory tests as well in different pavements subject to actual fires. As detailed below, test methods to determine the binder content of bituminous mixtures by ignition have been standardized both in the United States and Europe. With regard to actual fires, among others, important lengths of bituminous pavements were damaged seriously in tunnels like St. Gotthard, Mont-Blanc (1.2 km) and Fréjus (800 m), which had to be rebuilt later. At some points in the Mont-Blanc Tunnel the whole thickness (10 cm) of bituminous mixtures was destroyed by the fire, even affecting the reinforced concrete slab which supported the pavement [4].

It can also be mentioned that, in the Fréjus tunnel fire incident (2005), the behaviour of the bituminous pavement hindered the fire brigade since, as reported by the firefighters, the roadway melted under their feet in the vicinity of the fire [5].

Once the bituminous mixture burns, at least the upper part loses its cohesion and can easily disintegrate, making movement difficult or impossible.

In addition to the heat released by the ignition of the bituminous mixtures, another problem is the highly toxic gases and fumes generated during the combustion. According to a report by one of the commissions created after the Mont-Blanc fire, “heat was of such magnitude that the bituminous pavement inflamed, precipitating the suffocation of most of the victims” [6].

On the other hand, concrete is a non-combustible material, which does not emit toxic gases when subjected to fire and retains a very important part of its structural capacity even at very high temperatures. This has been verified in numerous laboratory tests, although the best proof is undoubtedly the behaviour of a large number of concrete structures in real fires. In this sense, a very interesting example was the Windsor building fire in Madrid (2005). In spite of the flames, that remained active for more than 24 hours and the high temperatures, over 1000 °C in some areas, the structure remained intact [7].

Another evidence of the good behaviour of concrete pavements in case of fire is the experimental tunnel of the Centre of Tests of Fire and Ventilation in Tunnels at San Pedro de Anes (Spain), considered one of the best facilities around the world on these issues. Since its opening in June 2005, numerous tests have been performed on its concrete pavement, including controlled fires of vehicles, with no significant distress to the concrete. (fig. 2)

In a laboratory, in order to realistically characterise the behaviour of a material when burning, it should undergo a temperature that may reproduce, in at least an approximate way, the one which may reasonably occur in a fire. Therefore, it can be useful to provide some information on the so-called fire curves, i.e. the curves of variation of temperature with time that have been defined in different regulations

Figure 2: Experimental tunnel of the Centre of Tests of Fire and Ventilation in Tunnels at San Pedro de Anes (Spain)

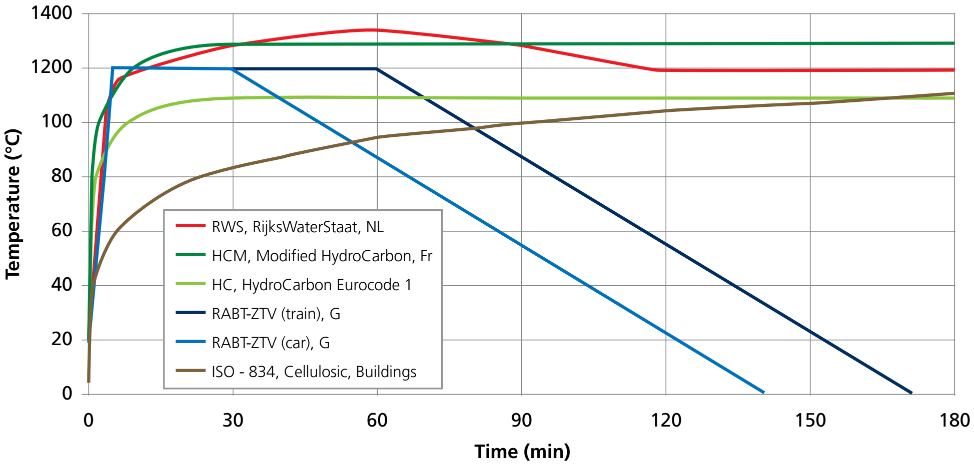


Figure 3: Fire curves. Evolution of the temperature according to the typology of fire

3. FIRE CURVES IN TUNNELS

In recent years a great deal of research has taken place internationally to ascertain the types of fire which could occur in tunnel and underground spaces. This research has taken place in both in service and disused tunnels, as well as in laboratory conditions.

As a consequence of the data obtained from these tests, a series of time/temperature curves [8] for different fire situations have been developed.

Standard fire tests to which specimens of buildings are subjected to are based on the use of the Cellulosic time/temperature curve, as defined in ISO 834.

Although the Cellulosic curve has been in use for many years, it soon became apparent that the burning rates for certain materials, e.g. petrol gas, chemicals etc, were well in excess of the rate at which for instance, timber would burn. As such, there was a need for an alternative exposure for the purpose of carrying out tests on structures and materials used within the petrochemical industry, and thus the hydrocarbon curve was developed.

The Hydrocarbon curve (HC) is applicable where small petroleum fires might occur, i.e. car fuel tanks, petrol or oil tankers, certain chemical tankers etc.

Derived from the above-mentioned Hydrocarbon curve, the French regulation asks for a more severe version, the so called HydroCarbon Modified curve (HCM).

The maximum temperature of the HCM curve is 1300 °C instead of the 1100 °C, standard HC curve.

The RABT-ZTV curve was developed in Germany as a result of a series of test programmes such as the European project FIRETUN (Fires in Transport Tunnels). In this curve, the temperature rise is very rapid: up to 1200°C within 5 minutes. The duration of the 1200°C exposure is shorter than other curves with the temperature reduction starting to occur at 30 minutes for car fires. The reduction for train fires only starts at 60 minutes. A 110 minutes cooling period is applied to both fire curves.

The RWS curve was developed by Rijkswaterstaat, the Ministry of Transport in the Netherlands. This curve is based on the assumption that in a worst case scenario, a 50 m³ fuel, oil or petrol tanker fire with a fire load of 300 MW could occur, lasting up to 120 minutes

The correctness of the RWS fire curve as a design fire curve for road tunnels was reconfirmed in the full scale tests in the Runehamar tunnel in Norway.

The RWS curve simulates the initial rapid growth of a fire using an oil tanker as the source, and the gradual drop in temperatures to be expected as the fuel load is burnt off.

Current Spanish legislation on safety in tunnels establishes that ventilation systems must be able to extract smoke for a standard fire type with a minimum power of 30 MW and a minimum flow of 120 m³/s, equivalent to assume the fire of a freight truck, as shown in table 2 [9].

TABLE 2 - FIRE LOADS IN TUNNELS

Vehicle	Thermal power (MW)	Maximum temperature in tunnel walls (°C)	Smoke release (m^3/s)
Car	2,5 – 5	400	20
2 – 3 cars	8	_	30
Van	15	_	50
Coach	20	800	60 – 90
Lorry	20 - 30	1000	60 – 90
Tanker	100 - 300	1200 - 1400	> 100

4. PROVISIONS REGARDING SAFETY IN TUNNELS

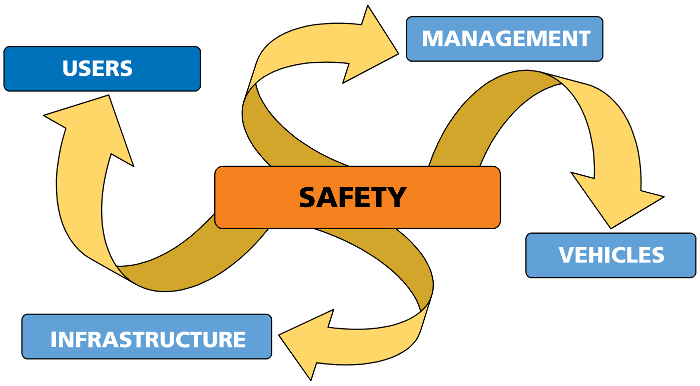
Due to concerns about the flammability of bituminous mixtures, in 2001 Austria banned the use of bituminous pavements in all tunnels longer than 1 km [10].

Subsequently, a minimum set of requirements for safety in tunnels was taken at European level, through the adoption of the Directive 2004/54/EC of the European Parliament and of the Council of the European Union of 29 April 2004 for tunnels in the Trans-European road network [11].

It is stressed in this Directive that safety in tunnels requires a number of measures relating, amongst other things, to the geometry of the tunnel and its design, safety equipment, including road signs, traffic management, training of the emergency services, incident management, the provision of information to users on how best to behave in tunnels, and better communication between the authorities in charge and emergency services such as the police, fire-brigades and rescue teams (fig. 4).

In Spain, as a result of the transposition into legislation of the above European Directive, as well as of the decision to improve safety in the road network and particularly in tunnels, the Royal Decree 635/2006 of 6 may was issued [12], on the conditions of design and operation of the tunnels in the State roads. It applies not only to tunnels in the Trans-European network but also to all State managed tunnels.

Figure 4: Areas of action for the improvement of safety in tunnels



Among the safety measures of this Decree, it is stated that:

"Unless duly justified reasons, in tunnels longer than 1,000 m, concrete pavements will be used"

Solutions different from those proposed in the Decree can be accepted only if they are impossible to be implemented in practice or have a disproportionate cost, and always provided the alternative leads to an equivalent or greater protection. The efficiency of such measures must be demonstrated through a risk analysis.

In relation to the concrete pavement as a measurement of safety and its possible replacement with another solution, for example through the use of bituminous mixtures, it should be stressed that:

- concrete pavements in tunnels are always a constructible solution. This does not mean difficulty or inconvenience for the contractor due to the fact that sometimes two types of pavements must coexist in the same work: one in the tunnel and a different one in sections in open air

- concrete pavements do not have a disproportionate cost; on the contrary, due to their minimum maintenance requirements, very often they are the cheapest option when total costs along 30 or 40 years are considered.

As mentioned above, other alternative pavements, e.g. with a bituminous wearing course, can be accepted provided that their safety against fire is equivalent or greater than that of a concrete pavement.

In order to be able to compare the behaviour of both bituminous mixtures and concrete in case of fire, the following paragraphs summarise the results of several tests carried out on this topic, as well as the conclusions drawn from a number of real cases.

5. BEHAVIOUR OF BITUMINOUS MIXTURES IN THE CASE OF FIRE

It has already been mentioned that the presence, as in bituminous mixtures, of a subproduct from oil refining, makes such mixtures easily flammable, and liable to significant degradation in case of fire.

Both the results next of several tests and observations of real cases that support this fact are presented below.

5.1 DETERMINATION OF THE BINDER CONTENT OF BITUMINOUS MIXTURES BY IGNITION TEST

For many years the combustibility of bituminous mixtures has been used to determine their binder content. In 1970 the Transportation Research Board of the United States developed a method for application at the jobsite using a butane burner [13]. In the early 1990s the National Center for Bituminous mixture Technology (NCAT), also from USA, developed a method of separating the binder from the aggregates by igniting a sample of the mixture which caused the binder to burn away, as an alternative to the more traditional method of solvent extraction. Due to the complete combustion of bitumen, the method can also be used to evaluate the composition of the mixture, because particle sizes and their proportion by weight can be determined, provided that disintegration of aggregate does not occur at the high temperatures reached [14].

This method is covered by ASTM D6307 standard [15] and in Europe by EN 12697-39 standard [16].

Depending on the type of bituminous mixture, the test lasts forty minutes from the beginning of warming. Normally a temperature of 400 to 550 °C is reached in the oven.

This test is a clear proof that bituminous mixtures burn, and at a temperature range lower than the maximum specified in the fire curves standardised for fires in tunnels.

In general, the determination of the binder content is performed on uncompacted samples. However, in an attempt to reproduce the conditions of a pavement during a fire, the authors of this document carried out a series of tests with specimens compacted with a system similar to that used in wheel track tests (fig. 5). Then the specimens were introduced in a special oven for these types of tests with some infrared heaters at its inner top and a integrated weighing system to continuously measure the mass loss of the bituminous mix during ignition. The test is automatically stopped when mass loss stabilises due to the complete combustion of the binder. Temperature and mass loss records are electronically stored and also printed by means of a built-in device.

After the test, specimens totally lost the cohesion provided by the binder, becoming a group of loose particles topped by a crust formed by the residues of the combustion of the bitumen, which could be easily broken off.

The curves showing the evolution of both temperature and mass loss in one of the tests are represented in fig. 6.

(a) Specimen of bituminous mixture before being tested

(b) Introduction of the specimen in the oven

(c) Inside of the oven with the infrared heaters at the top

(d) Ignition of the bituminous mixture during the test

(e) Aspect of the specimen after the test

(f) Once the test is completed the bituminous mixture loses completely its cohesion and can be easily broken off

Figure 5: Ignition test performed on a specimen of bituminous mixture in a oven used to determine the binder content by ignition

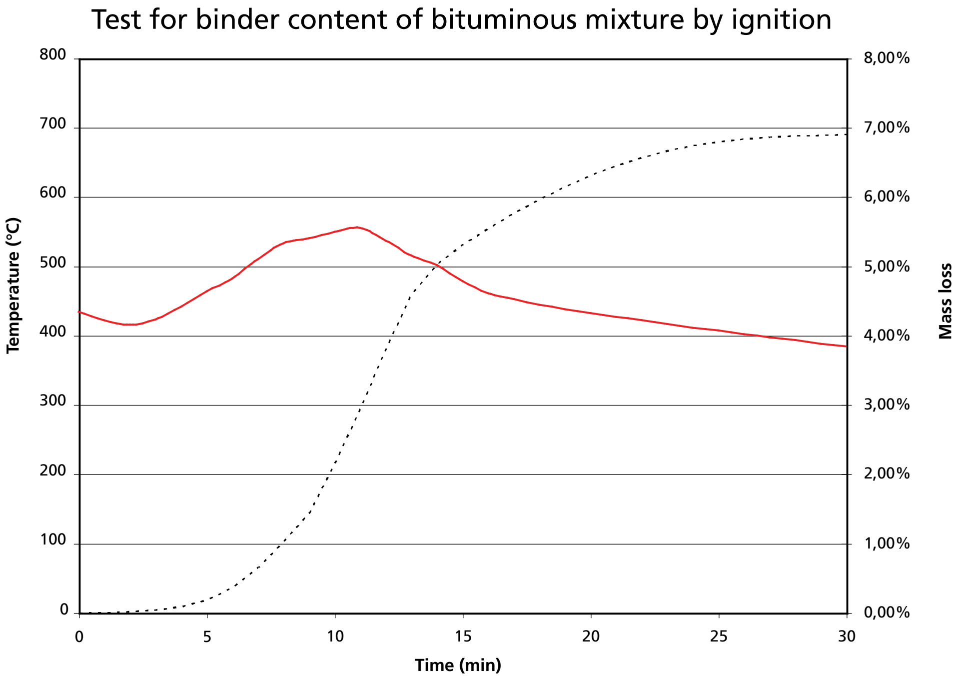


Figure 6: Curves of evolution of temperature and mass loss in an ignition test of a bituminous mixture

5.2 UNIVERSITY OF CERGY-PONTOISE (FRANCE)

The Laboratory of Materials Science and construction of the Cergy - Pontoise University (France) conducted a detailed experimental study on the behaviour against fire of a number of specimens of bituminous mixture and concrete. Results were published in 2003.

One of the merits of this work is that it was the first one where the behaviour of bituminous mixtures in case of fire was studied in a controlled way, subjecting the specimens to a standard fire curve (ISO 834) and measuring the evolution of temperatures at different heights by means of thermocouples. For comparison the same tests were carried out on concrete specimens [17].

The study details the characteristics of the materials used (binder content and other properties), the dimensions of the specimens (most of them prisms of 50 x 18 x 5 cm), the oven used to heat them, the position of the thermocouples and the evolution of the temperature in the specimens. Gases emitted during combustion of the bituminous mixture were also analyzed [18]. The information is supplemented with numerous photos and graphs. Some of them are reproduced in figures 7 to 11.

The most relevant conclusions of this study are the following:

- Concrete, due to its composition, is stable in fire situations. It is not flammable, and therefore does not contribute to the fire load which, inside the tunnel, determines the risk of fire and the magnitude and consequences arising from it.
- Bituminous mixtures have a high calorific value, which increases both fire load and temperatures during a fire. They ignite between 428 °C and 530 °C.
- Bituminous mixtures do not maintain their mechanical characteristics in case of fire. Combustion results in disintegration and loss of cohesion - the binding effect of bitumen is irreversibly lost.

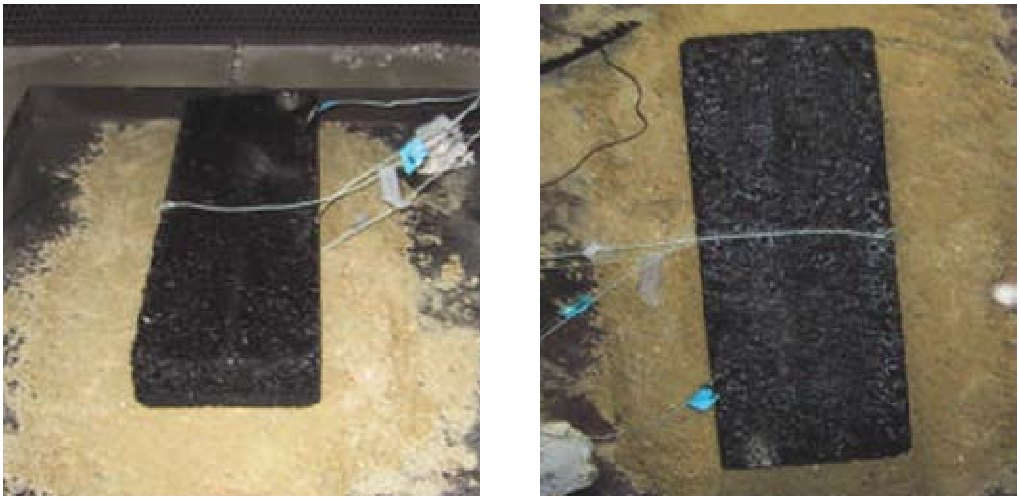


Figure 7: Specimen of bituminous mixture before being tested (Cergy – Pontoise University)

Figure 8: Specimen of bituminous mixture during its ignition (Cergy – Pontoise University)

Figure 9: Specimen of bituminous mixture after the ignition test (Cergy – Pontoise University)

Figure 10: Specimens of bituminous mixture (left) and concrete (right) after the ignition test (Cergy – Pontoise University)

- A bituminous pavement reaches very quickly a high temperature compared to a concrete pavement.

- A bituminous pavement, 5 minutes after being heated, emits suffocating and toxic gases (carbon monoxide and dioxide, aldehydes, methanol, propanol-2, acetone, benzene, toluene, sulphur dioxide and acetic acid, among others), worsening fire situation.

The appearance of the bituminous mixture specimens was similar to those of the tests for the determination of binder content by ignition (fig. 5).

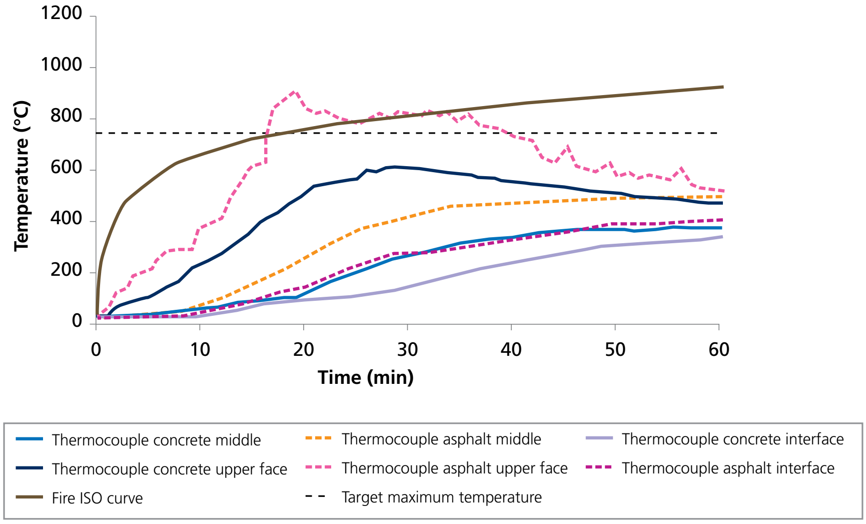


Figure 11: Temperatures measured in bituminous mixture and concrete specimens subjected to an ISO 834 fire curve (Cergy – Pontoise University)

5.3 FEDERAL HIGHWAY RESEARCH INSTITUTE OF GERMANY (BASt)

The Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) of Germany published in 2003 a bibliographic study on the behaviour of bituminous and concrete pavements in tunnels in case of fire [19]. It only analyses German documents.

Details of a series of fires in road tunnels from 1949 until 2000 are provided. It is indicated that distress in the bituminous layers was several centimetres in depth.

It is also mentioned that as a result of some inquiries conducted after the Mont-Blanc fire, it was still unclear why eight vehicles parked at a distance of about 300 m from the fire on the Italian side had burnt. Since the ceiling of the gallery in those 300 m hardly showed damage, it seems likely that the combustion of the vehicles occurred by a spread of the fire in the bituminous mixture at a high temperature.

Some tests carried out in Germany on bituminous pavements are described. The results are highly questionable, since due the way heat was applied (for example, by burning wooden crates stacked on the pavement) the temperature of the surface of the bituminous mixture did not exceed 400 ° C. Not surprisingly, the bituminous mixture was damaged in a thickness of just 1 cm, which does not correspond with what had been observed in real fires.

5.4 SCIENTIFIC AND TECHNOLOGICAL CENTRE OF CONSTRUCTION OF FRANCE (CSTB)

The Scientific and Technological Centre of Construction of France (Centre Scientifique et Technique du Batiment, CSTB) conducted a bibliographic analysis and an experimental study on the behaviour of bituminous pavements in cases of fire in road tunnels [20] [21] [22].

In the tests, bituminous specimens (60 x 40 x 10 cm) were placed under a radiant panel (60 x 60 cm) and subjected to a heat flow between 20 and 50 kW/m^2.

Each test was terminated when a thermocouple, placed inside the specimen 15 mm below the upper surface, registered 300 °C. This temperature is lower than that at which bitumen ignition occurs, so these tests, too, failed to represent what really happens during a fire in a road tunnel.

Even at these low temperatures, most specimens lost internal cohesion, being reduced to a crumbled group of particles, while on the surface a crust of material was formed. This behaviour is similar to that observed in ignition tests to determine binder content (fig. 5) or in those carried out at the Cergy – Pontoise University (fig. 10). Consequently, the crust does not prevent the rest of the thickness from burning, but on the contrary, it is a result of the combustion.

During the tests, apart from the inflammation of the specimens, the formation of a dark, dense and strong smelling smoke was observed.

Even in low severity cases, the lack of protection provided by the “inert crust” is easily verifiable. For example, the degree of distress in an urban pavement after a car fire can be seen in fig. 12.

5.5 SAMARIS PROJECT (SUSTAINABLE AND ADVANCED MATERIAL FOR ROAD INFRASTRUCTURE)

SAMARIS was a European research project involving 23 partners, partly financed by the European Community. It was developed from 2002 to 2005. It was split into two main topics: structures and pavements. One of its main objectives was to encourage the use of alternative and recycled materials in pavements, identifying how they can be selected and tested in order to ensure satisfactory behaviour, both from the environmental and functional points of view.

Among the tasks of this project was assessment of the reaction to fire of different materials for pavements [23]. There were doubts whether tests specified in EN 13501-1: 2002. “Fire classification of construction products and building elements. Part 1: Classification using test data from reaction to fire tests” [24] would provide the level of discrimination required to differentiate between pavement types. Therefore, it was decided to subject three different types of bituminous mixtures (porous bituminous mixture, dense bitumen macadam, mastic bituminous mixture) to two tests according to the following standards:

- EN ISO 9239-1 “Reaction to fire tests for floorings – Part 1: Determination of the burning behaviour using a radiant heat source” [25], which is one of those prescribed in the above-mentioned standard EN -13501-1

- ISO 5660-1 “Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method) " [26] (fig. 13).

Among the results of the project the following ones can be highlighted:

- The critical heat flow to start a sustained combustion of a dense bituminous mixture was about 21 kW/m^2, that is, in the range of values (15-25 kW/m^2) recorded on tests with cars on outdoor fires.

- This value is typically twice the level of irradiance provided in the EN ISO 9239-1 flooring test. For this reason, this test method does not provide any differentiation in fire performance. The results obtained with this test cannot be used to evaluate the behaviour in fire of bituminous mixtures, unless some modifications are introduced on the test apparatus.

- Time to start sustained flaming decreases notably as the irradiance level increase: at 35 kW/m^2 it can exceed 10 minutes, whereas at 75 kW/m^2 it is less than 1 minute.

It is also stressed in the study that in a confined area such as a road tunnel, the heat flux radiated back from the hot smoke layer and the tunnel walls would increase the probability of the pavement igniting and making a more significant contribution to the extent of the fire than in an open road scenario.

Figure 12: Distresses produced in an urban pavement by a car fire

Figure 13: Ignition of a specimen of bituminous mixture in the cone calorimeter test

5.6 BRE CENTRE FOR FIRE SAFETY ENGINEERING OF EDINBURGH UNIVERSITY

The BRE Centre for Fire Safety Engineering of the University of Edinburgh has developed a research project into the fire behaviour of bituminous mixture road surfaces. It also uses the cone calorimeter method [27], aiming to incorporate the results into Dynamic Computation of Fluids (DFC) models to enable accurate simulation of tunnel fire scenarios. Cylinder specimens of stone mastic bituminous mixture were exposed to heat flows of 60, 50, 40 and 30 kW/m^2. The bitumen content of the samples was 6.3% (by mass). Dimensions of cylinders were 100 x 100 x 60 mm.

The main results of the tests were the following:

- The critical heat flux for ignition of bituminous mixture is less than 40kW/m^2. Heat fluxes of this magnitude are certainly produced in tunnel fire incidents and experiments.

- The structural properties of the material were destroyed during the test. The post-test material had crumbled and was easy to break.

- The heat release rate increased markedly as the incidental heat flow increased. At the value of 60 kw/m^2 of the latter, a heat release rate near 100 k/Wm^2 was observed. With higher flows this rate is expected to increase as well.

- Typical bituminous mixtures can potentially ignite during tunnel fires and produce heat release rates comparable to those of other fuel sources commonly found in tunnels (e.g. cars).

It should be outlined that these results were obtained with specimens that were only 60 mm high. It has been noticed in real fires than the depth of the mixture affected by the flames can be higher than that, which in turn will also result in an even higher heat release rate.

The report of the results mentions that during the fire tests in the Runehamar Tunnel in Norway in 2003, heat fluxes were recorded at various locations near to the fire sources (simulated heavy goods vehicle trailers). In the first three tests (one loaded with wood and plastic pallets, the second one loaded with wooden pallets and mattresses and the third one loaded with furniture) this critical heat flux was exceeded at locations on the roadway, downstream of the fire location, where the maximum fluxes recorded were about 280, 200 and 75 kW/m^2, respectively. Heat fluxes above this critical limit were also recorded 5 m upstream of the fire location in the first test, where the peak flux almost reached 100 kW/m^2.

Consequently, even if bituminous mixture ignition is limited to the area immediately downstream of a heavy goods vehicle fire, this may still involve an area of roadway greater than 50 m^2, so the heat release rate due to the bituminous mixture may be 5 MW or greater, which is equivalent to at least one or two car fires. In severe cases, the bituminous mixture under the vehicle, adjacent to it and upstream of it may also be affected.

5.7 BEHAVIOUR OF BITUMINOUS MIXTURES IN REAL FIRES

Conclusions obtained in tests are in agreement with the behaviour of bituminous mixtures in real fires, where it has been observed that even at some distance from a burning vehicle temperatures are able to cause the combustion of the bituminous mixtures.

It has been mentioned that in a confined area such as a road tunnel, the heat flux radiated back from the hot smoke layer and the tunnel walls would increase the probability of the pavement igniting. In this respect it should be remembered that among other examples, serious fire damage occurred in significant lengths of the bituminous pavements in St Gotthard, Mont-Blanc (1,2 km) and Fréjus (800 m) tunnels, that had to be replaced later on. In the fire in the Mont-Blanc tunnel (1999) distress affected 1200 m of carriageway, whereas 32 cars and 2 trucks burnt. Their combined length is less than 250 m.

Mention also should be made of the fact that in the Mont-Blanc fire, eight vehicles parked at a distance of about 300 m from the fire on the Italian side burnt [14]. Since the ceiling of the gallery in those 300 m hardly showed damage, it seems likely that the combustion of the vehicles occurred by a spread of the fire in the bituminous mixture at a high temperature.

Even without igniting the bituminous mixtures, high temperatures can lead to excessive softening. Certainly, the behaviour of the asphalt pavement hindered the fire brigade in the Fréjus Tunnel fire incident (2005); as reported by the fire-fighters, the carriageway melted under their feet in the vicinity of the fire [5].

6. BEHAVIOUR OF CONCRETE AGAINST FIRE - SPALLING PHENOMENA

Concrete is non-combustible. It has been said, rightly, that among usual construction materials, it is the most resistant against fire [28]. Many examples such as the Windsor building fire in Madrid have proved this. Not only did the concrete structure of the building remain standing, (thus avoiding a much greater catastrophe) but also its demolition was difficult and costly. This proves that, after the fire, concrete in the structure retained a considerable strength.

This good behaviour of concrete against fire has not only been observed in buildings but also in other types of works, like tunnels. The conclusion drawn from a number of real cases is clear: tunnels sustained or lined with concrete (precast, formed or sprayed) are structurally safe against fires. No cases of structural collapses in tunnels have been reported, neither references of deaths resulting from to structural damages.

However, when concrete is subjected to high temperatures, their components can exhibit important properties [29]:

- once 100 °C is reached, free or capillary water present in the mass starts to evaporate, delaying further heating
- between 200 °C and 300 °C water loss is complete, without alterations in the hydrated cement structure or any notable decrease of the strength
- between 300 and 400 °C cement gel loses water; an important decrease in strength is noticed and the first cracks may appear on the surface
- at 400 °C a part of the calcium hydroxide produced by the hydration of the cement silicates transforms into quicklime
- by 600 °C aggregates begin to expand. This results in internal stresses that initiate the disintegration of the concrete. Volume increase is higher with siliceous than with limestone aggregates, since the thermal expansion coefficient of the former is on average 35% higher.

Although some variation in reduction of strength with temperature depends on the type of concrete, being smaller in the case of limestone aggregates, it can be safely assumed that up to 500 °C, strength decrease is not significant. For this reason, when estimating the remaining load-bearing capacity of a section that has been exposed to fire, the Spanish Code EHE-08 for Structural Concrete [30] allows the use of a reduced section obtained eliminating, for calculation purposes, only those sections where temperatures over 500 °C were reached.

An important remark is that temperatures mentioned in previous paragraphs have to be the real concrete temperatures and not those of the environment or the flames. For this reason the consequences of a fire to both the strength and structural capacity of a concrete element are less important than expected.

On the other hand, concrete is a material with a low thermal conductivity.. The rate of increase of temperature through the cross section of a concrete element is slow, and so internal zones do not reach the same high temperatures as a surface exposed to flames. At depths of a few centimetres inside the temperatures reached do not decrease excessively concrete strength. This is another reason for the excellent behaviour of concrete structures in fires.

In addition it should be stressed that temperature progression inside a pavement is lower than in other structural elements, such as a beam or a column, which can be heated on various faces at the same time. As shown in fig. 15, taken from the abovementioned EHE-08 Code, temperature in a slab at a 2 cm depth can be 300 or 400 °C lower than that of the surface, and at 4 cm, 500 °C or 600 °C lower. When the temperature of the surface reaches a value of 850 °C, only the top two centimetres are subjected to temperatures over 500 °C. In this regard, it is worth mentioning that the EHE-08 Code points out that curves in fig. 14 are very conservative.

For this reason, in many cases damages caused by fire are restricted to a thin surface layer.

Apart from loss of concrete strength, another problem that can arise during a fire is spalling, i.e. the breaking off of layers or pieces from the surface.

A number of theories have been developed to explain spalling occurrence [31]:

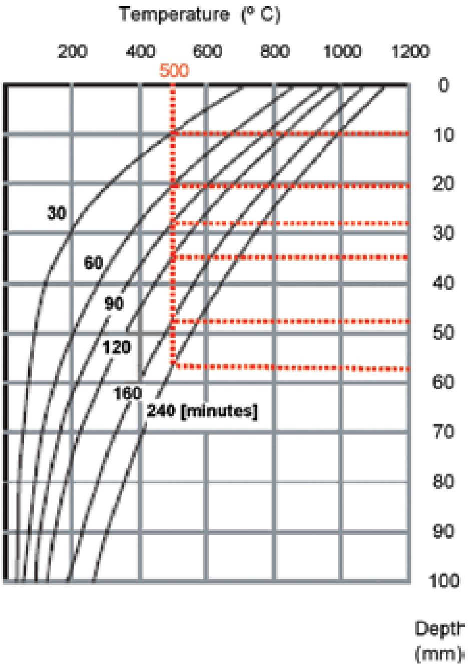


Figure 14: Curves of variation of temperature inside a concrete slab during a fire (Spanish EHE-08 Code)

- Pore pressure rises due to evaporation of water when the temperature increases. Consequent expansion, as well as possible outward migration of both vapour and water, are more restrained when concrete structure is more compact, which is usually the case with high strength concrete.

- Compression of the heated surface due to restrained thermal expansions in the cross section. High compressive stresses can be attained.

A combined effect of both mechanisms should not be disregarded as the cause of spalling in many cases.

High strength concretes are more sensitive to fire-related spalling, resulting in some cases in explosive phenomena. A number of tests have proved the beneficial effects in this regard of incorporating polypropylene fibres, which melt at about 160 °C and provide channels in the concrete for moisture to escape [29], thus reducing pore pressures and the risk of spalling. Another possibility which has been suggested is the use of air-entraining admixtures, since they create a great number of microscopic air cells. These relieve internal pressure on the concrete by providing tiny chambers for the expansion of water [31]. This is a common practice with concrete exposed to freezing in order to withstand the internal pressures due to the water volume increase when it turns into ice.

Another factor that can influence spalling is the difference in thermal expansion between concrete and reinforcing bars. Usually this is not an important issue in pavements, since either they are made of plain concrete or, in the case of continuously reinforced concrete pavements, reinforcement is placed at mid-depth, so they have sufficient concrete cover (normally between 8 and 13 cm) to minimise temperature changes at the reinforcement level and to withstand internal pressures produced by the expansion of the bars. For the same reason, another problem that can arise as a consequence of a fire in a concrete structure - the loss of bond between concrete and reinforcing bars - is less likely in continuously reinforced concrete pavements.

Furthermore, in pavements there are no gravity or pressure effects of the surrounding ground, which can contribute to spalling.

The influence of mechanical strength on the behaviour of concrete against spalling has been verified in real fires as well as in laboratory tests. Although not a roadway tunnel, it should be mentioned that extensive spalling of the lining occurred in the Channel tunnel fire (1996), where high strength concrete (80 MPa) was used. On the other hand, spalling was much less severe in the Mont-Blanc and St. Gotthard tunnels, built many years ago, and probably for this reason with concrete of a lower quality [28].

Other real cases have shown the satisfactory resistance to spalling of normal strength concrete, with compressive strength about 30 MPa at 28 days.

Concerning laboratory tests, worthy of mention are those performed in France in the Feu-Béton (Fire-Concrete) research project, whose results were published in 2006 [31]. It was concluded that concretes with a compressive strength up to 60 MPa did not exhibit significant spalling when subjected to an ISO 834 standard fire curve.

Compressive strength values for pavement concrete range from 25 to 45 MPa, thus staying below 60 MPa. Therefore spalling, as consequence of a fire, should not be an important problem in concrete pavements.

The authors of this document have carried out some tests on the behaviour against fire of concretes for pavements using an oven intended primarily to determine by ignition the binder content of bituminous mixtures. The specimens had dimensions of 30 x 5 x 5 cm and before being tested they were stored for several weeks in a curing chamber to saturate them. When subjected to temperatures between 350 and 450 °C for 40 minutes1, no spalling was observed (fig. 15), only a reduction in mass as a consequence of the evaporation of the absorbed water.


Figure 15: Specimen of concrete for pavements, stored in a curing chamber and then subjected to temperatures between 350 and 450°C in an oven

It can be concluded that spalling in concrete pavements as a result of fire, is likely to be much less severe than in other parts of the tunnel, such as the lining or a ceiling.

Concrete not affected by either high temperatures or spalling retains practically all its strength, forming a sound substrate. For this reason, repair of defects can be carried out by means of partial-depth patches or, if necessary, with a thin bonded concrete overlay, after milling some centimetres of the pavement.

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[1] Spalling, in the event of it, usually appears during the first 30 minutes after fire starts

7. OTHER ADVANTAGES PROVIDED BY CONCRETE PAVEMENTS IN TUNNELS

Concrete pavements in tunnels present some other advantages giving safety benefits:

- concrete pavement brightness (fig. 16) ensures better visibility for road users. Moreover it requires less electric lighting, thus reducing energy consumption.
- a reduced braking distance due to high friction on the road.
- a decrease of possible accidents during maintenance operations, since they are not frequent.

In addition, the positive effect of concrete pavements in reducing fuel consumption should be stressed. In tests conducted in Sweden, reductions of 1 % with cars have been recorded; and in a number of tests in other countries, 6.5 % with trucks [32] [33]. Higher fuel consumption on bituminous pavements is attributed to their higher rolling resistance [34].

Figure 16: Juan Carlos I Tunnel (Spain)

8. CONSTRUCTION OF CONCRETE PAVEMENTS IN TUNNELS

Figure 17: Cylinder finisher

8.1 EQUIPMENT

In principle, all the techniques used to construct concrete pavements outdoors can also be employed in tunnels.

Leaving apart the construction with form-riding vibrating screeds, the most common machines are the following ones:

- cylinder finishers, also employed in bridge decks and canal linings, usually running on fixed forms (fig. 17)

- multi-purpose machines, most often employed to build concrete elements such us curbs or safety barriers, but also able to construct pavements up to 6 m wide

- slipform pavers

Figure 18: Construction by half widths

Figure 19: Construction by full width

Among slipform pavers, a distinction can be made between those with a maximum working width up to 6 m - those usually employed in the construction of road carriageways by half-widths (Fig. 18) - and those with a capacity to construct paving widths of from 2.5 – 3 m up to maximum widths of 8.5 – 10 m (Fig. 19). There are also larger machines for the construction of highways and airport pavements, which can reach working widths of 16 m.

Both multi-purpose machines and slipform pavers move on caterpillar tracks. Generally they are guided by grade and steering sensors in contact with stringlines supported by regularly spaced stakes. These machines can also be controlled by automated 3-D systems.

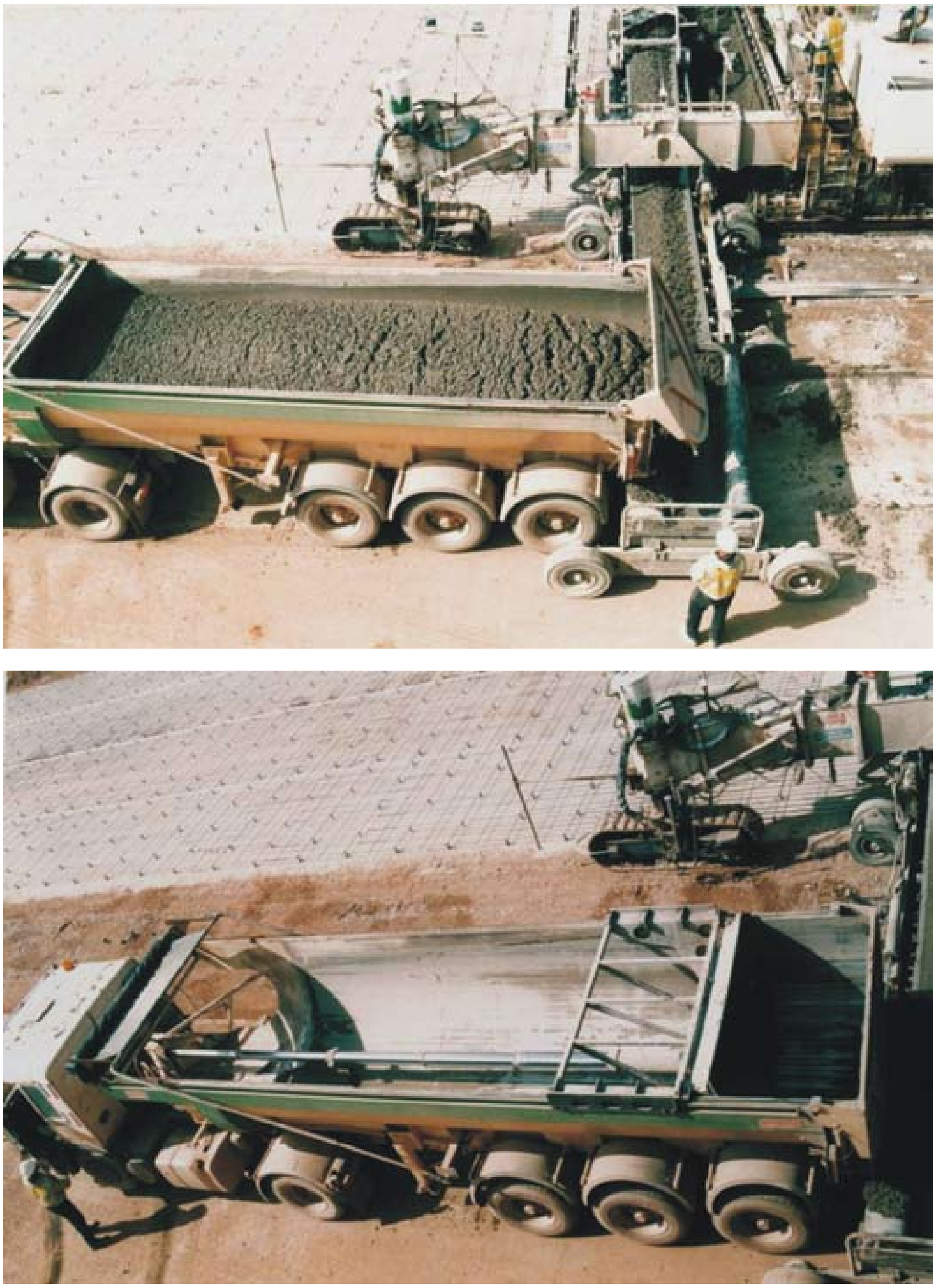
8.2 PARTICULARITIES OF THE EXECUTION OF CONCRETE PAVEMENTS IN TUNNELS

The main constraints arise from the limitation of side and vertical clearance, which can influence the supply of concrete as well as other elements, such as those used to hold the stringlines.

Sometimes it is necessary to keep the tunnel open to traffic, which will require the construction of the pavement by half widths, and occasionally to use fast – track concreting systems.

Figure 20: Side dump truck

Figure 21: Ejector truck



8.2.1 CONCRETE SUPPLY

The fastest system to supply concrete is by means of dump trucks discharging directly in front of the paver. Obviously, for this purpose the subbase must be free of anything which can hinder or prevent the movement of vehicles - this generally happens with the bars of continuously reinforced pavements.

When the use of normal dump trucks is not possible due to the existing clearance, alternative solutions include the following:

- concrete mixer trucks (although the output may be reduced: the discharge time of a truck with a capacity of 8 m^3 can exceed 10 minutes when long delivery chutes are needed)

- side dump trucks (fig. 20)

- ejector trucks, with a box and a piston which expels the concrete into the paver (fig. 21).

A backhoe can also be used to ease the unloading of the dump truck so that the box of the truck does not have to be raised completely.

Complementary to the previous systems, mention should be made of the possibility of the use of mobile transfer conveyors to allow concrete to pass over elements placed in front of the paver (e.g. dowels). A similar option can be adopted when constructing the pavement in two layers simultaneously. For the supply to the rear paver of concrete for the upper layer, a conveyor belt assembled on the front paver can be used (fig. 22).

Figure 22: Two layer pavement: supply of concrete of the upper layer

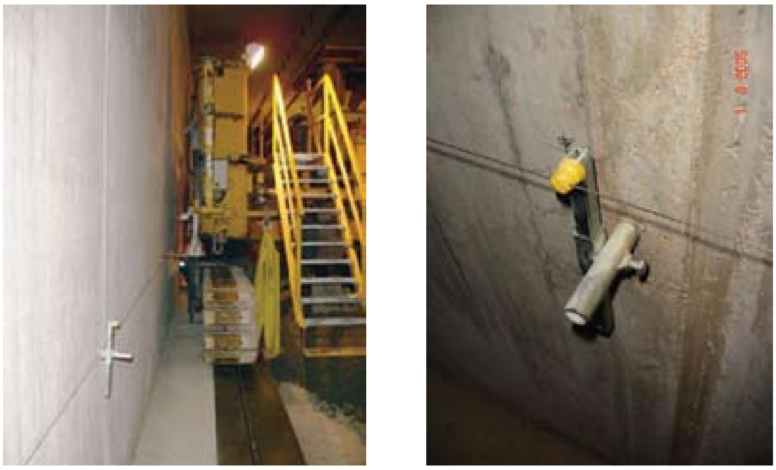


Figure 23: Stakes to support the stringlines fixed to the walls

8.2.2. LATERAL SPACE LIMITATIONS

Pavers need enough lateral space for both the caterpillar trucks on which they are moved (as with slipform pavers), and for positioning the guidance elements. These can be either a thread or tense wire (slipform pavers) or, in the case of cylinder finishers, rails on which flanged wheels circulate.

Sidewalks are frequently provided in road tunnels. This makes it difficult to place the stakes to support the stringlines. A possible solution is to fix such supports to the walls (fig. 23). When using cylinder finishers, a similar system can be adopted for the rails to guide the wheels.

Another possibility is the use of 3D systems, since in this case stringlines are not needed. This method has already been employed both inside tunnels and in pavements outdoors.

Sometimes sidewalks are hollow (i.e. to allow ducts to be installed) and if tracked vehicles have to circulate on them, they must be duly protected to avoid breakages.

Figure 24: Continuously reinforced concrete pavement constructed by half widths

8.2.3 CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

Continuously reinforced concrete pavements (CRCP) are widely used for heavily trafficked motorways due to their significantly reduced maintenance costs when they are designed and built correctly. Their durability can far compensate for the extra cost introduced by the reinforcement.

As trucks cannot circulate on the reinforcement, some of the alternative solutions are the following:

- execution by half widths, which must be connected with tie bars (fig. 24)
- mechanical steel placement (tube-feeding). In this case, the proper number of longitudinal bars is pre-spliced out ahead on the base and threaded through a battery of plan-spaced tubes mounted on the paver, where they are held at the specified vertical and horizontal positions as the concrete is placed between the tubes (fig. 25). To provide sufficient clearance and allow concrete delivery trucks to run on the base, reinforcing bars are grouped either on its central part and/or at its edges. Concrete is dumped into feeding equipment with one or to receiving hoppers, from where it is directed towards one or two conveyor belts. The flow of concrete is then discharged in front of the slipform paver. Length and elevation of the conveyors are chosen to pass over the transition area where reinforcing bars shift from their initial position towards the tubes.

Figure 25: Mechanical steel placement in a continuously reinforced concrete pavement

8.3 CONCRETE FOR PAVEMENTS IN TUNNELS

In principle, the requirements for concrete used in tunnel pavements are not different in any significant way to those for pavement concrete outdoors. However, some measures may help to optimize the behaviour of concrete in a fire:

- use of limestone aggregates, which have a smaller expansion coefficient than siliceous ones. In this case, to obtain durable antiskidding characteristics, aggregates in contact with wheels of vehicles must have an adequate wear resistance. When the surface texture is to be obtained by brushing or tining the fresh concrete, this is accomplished using sands with a content of siliceous particles not less than 35 %. If the pavement has an exposed aggregate surface, obviously limestone aggregates are restricted to the bottom layer, whereas in the upper one (or in the whole thickness if the pavement is constructed in one layer) coarse aggregates must have a polished stone value over 0.50.

- use of air entrainers, which create pores acting as expansion chambers that decrease the internal pressure which results from the increase of temperature caused by a fire.

Air entrainers also contribute to improved concrete workability. With respect to this last point, it should be stressed that mix designs of concretes for tunnel lining may not be convenient for pavements if sand obtained crushing the excavation products is used, Frequently this type of sand contains an excessive amount of fines, giving rise to “sticky” concretes which stick to the screeds of the pavers or to other finishing tools. This usually results in a poor surface evenness

- When the pavement must be put into service within a short time, or if it is necessary to allow construction equipment or job traffic to circulate on on an already executed band it, it is possible to use concretes with an accelerated hardening time which can reach the necessary strength in a few days or even hours.

8.4 CONDITIONS TO OBTAIN A GOOD SURFACE EVENNESS

The rules to obtain a proper surface evenness on a concrete pavement are mainly based on the choice of an adequate mix design and also on attention to consistency in the processes of manufacturing and laying concrete. Important factors include the following :

- homogeneous concrete, without variations in consistence

- paver in good condition

- manufacturing of concrete to satisfy the expected progress of paving

- transport of concrete from the mixplant to the jobsite well organized

- continuous supply of concrete to the paver in accordance with its advance, avoiding interruptions

- correct guidance of the paver

- stable tracks must be provided for the paver

- regular progress of the paver

- avoidance of hand finishing operations behind the paver.

9. SUMMARY AND CONCLUSIONS

In the preceding paragraphs, the behaviour against fire of two materials for pavements, bituminous mixtures and concrete, have been analyzed with the aim of comparing the safety they provide to a tunnel in a fire.

Concrete is an incombustible material, which does not release smoke or toxic gases nor increase the fire load during a fire. The thickness where significant strength losses can occur is limited to a few centimetres. Spalling is not important in pavements, where no ultra high-strength concretes are used.

With regard to bituminous mixtures, the presence of a subproduct from oil refining, such as bitumen, which is highly combustible, does pose a number of questions, listed below, together with the answers drawn from both real fires and laboratory tests:

Can bituminous mixtures burn?

Yes, as soon as bitumen combustion temperature is reached in the bituminous mixture (between 400 and 500 °C). Making use of this property, methods to determine its binder content by means of ignition have been developed.

Are temperatures where bituminous mixtures start burning reached during a fire in a tunnel?

They are actually generally higher, not only in the free section but also in the pavement. It should be stressed that in a confined area such as a road tunnel, the heat flux radiated back from the hot smoke layer and the tunnel walls would increase the probability of the pavement igniting and making a more significant contribution to the spread of the fire than in an open road scenario.

What effects does the bituminous mixture combustion have?

The high calorific value of bitumen results in an increase in the fire load. On the other hand, shortly after combustion begins, smoke and toxic gases are released, which may result in the suffocation of victims. Eventually, bituminous mixtures lose their cohesion, deteriorating into a mass of unbonded particles.

Does burning of bituminous mixtures affect only the surface of the pavements?

The depth where the temperature necessary for combustion occurs usually reaches several centimetres. In the Mont Blanc tunnel fire the whole thickness of 10 cm of bituminous mixtures burnt at some points. The greater the affected thickness, the more the increase in the fire load and the smoke and gases released.

Is bituminous mixture combustion limited to the area immediately under burning vehicles?

Several factors, such as ventilation, or the heat reflected on the walls and the roof of a tunnel can lead to the temperature being high enough to cause ignition of bituminous mixtures even well away from the focus of the fire. Therefore, the length of the affected area can be much larger than that of the burnt vehicles. In the Mont Blanc tunnel fire 32 cars and 2 trucks were destroyed by fire. Their total length was less than 250 m, but distress occurred along 1,200 m of the pavement. The heat produced by the combustion of 50 additional m^2 can be equivalent to the one produced by two or three cars burning.

Can bituminous pavement make the fire to spread to other vehicles away from the initial focus?

In the Mont Blanc tunnel eight vehicles parked at a distance of about 300 m from the fire were destroyed by fire. The ceiling of the gallery along that length showed almost no distress: Therefore it seems likely that the combustion of the vehicles was due by a spread of the fire in the bituminous mixture at a high temperature.

What other effects can occur in bituminous mixtures because of the heat generated during a fire?

Even without igniting the mixture, the increase in temperature can cause the bituminous mixture to soften, hindering the access of rescue or fire-extinguishing teams. In the Fréjus tunnel fire, firemen reported that the bituminous mixture melted under their feet.

To justify the use of bituminous mixtures in tunnels It is widely claimed that only a thin surface layer ignites during a fire and that an inert crust is created which prevents fire from progressing inside. This does not reflect what actually happens. In reality, in real fires, a thickness of several centimetres of bituminous mixture burns, and it is combustion residues which create this crust which virtually has no cohesion.

As a summary, it can be concluded that in tunnels, in case of fire, concrete pavements provide a much higher degree of safety than bituminous mixtures.

Due to concerns about the flammability of bituminous mixtures, in 2001 Austria banned the use of bituminous pavements in all tunnels longer than 1 km.

In Spain, the Royal Decree 635/2006 of May 26 on conditions of design and operation of the roads tunnels managed by the State Administration prescribes that, except for duly justified reasons, in tunnels over 1,000 metres a concrete pavement will be used. Other alternatives can be applied only if they result in an equivalent or greater protection.

In view of the previous considerations, the replacement of the concrete pavement by a bituminous one does not meet this requirement.

Similarly, the French Federation of Firemen states that “simple logic should impose the replacement of bituminous mixtures by a totally neutral material as concrete” [35].

For its part, the International Technical Committee for the Prevention and Extinction of Fire (CTIF) [1], an organization representing five million firemen and the most important worldwide, recommends that “road pavement should be incombustible, emit no toxic smoke and be of clear colour which improves visibility. Concrete should therefore be preferred as material to the traditionally used bituminous mixture pavements which ignite and emit toxic gases”.

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