Title: The innovative approach for using pavement as a fire prevention measure in tunnels

Authors:

Mariusz Jaczewski, PhD, Gdansk University of Technology, mariusz.jaczewski@pg.edu.pl, 0000-0003-4722-2957

Marek Pszczola, PhD, DSc, Gdansk University of Technology, marek.pszczola@pg.edu.pl, 0000-0002-6401-7966

Dawid Ryś, PhD, Gdansk University of Technology, dawid.rys@pg.edu.pl, 0000-0002-7252-8002

Piotr Jaskuła, PhD, DSc, Gdansk University of Technology, piotr.jaskula@pg.edu.pl, 0000-0002-1563-2778

Abstract:

The paper consists of two main parts: first presents study regarding the typically used pavement structures in tunnels and the second part: the first fire trials of the poroelastic SEPOR (Safe, Eco-friendly POroelastic Road Surface) mixture which was designed to be used among other uses in tunnels. In the first part of the paper different pavement materials, such as cement concrete, asphalt concrete, stone mastic asphalt and porous asphalt are analyzed from the point of view of fire resistance. The paper summarize the wide and comprehensive literature review (both technical reports, conference presentations and journal articles) and presents advantages and disadvantages of specific pavement types. In the paper also the perspective improvements and advantageous mechanisms are presented for asphalt pavements. The literature review helps the administration and technical staff to get to know the properties of each pavement and chose the best one for their application. The second part of the paper present the innovative poroelastic SEPOR pavement, which is designed to slow down the initiation of the fire. The mixture is designed using the mineral aggregate, rubber aggregate and highly SBS-polymer modified bitumen. The mixture is designed to contain at least of 15% of mass of rubber aggregate and with target of voids around 20%. Such composition allows to slow down the ignition of the fire and allow people to have more time for evacuation. The paper presents two fire trials which were conducted for the SEPOR pavement. First trial was designed to measure the temperature increase during fire on the level of the vehicle floor. The second trial was designed to measure both the temperature of the vehicle and the time of fire ignition and the development of fire. During second trial real vehicles were used in the test. The measurement were direct for the real fire conditions. The first trial showed that the SEPOR pavement shows lower trial of fire temperature development. The measured temperatures were lower and increase slower in comparison to the pavements typically used in tunnels, such as stone mastic asphalt (SMA) or cement concrete. Also the SEPOR pavement showed in some specimen the possibility to dampen the flames during the fire. The second trial showed that SEPOR pavement presents superior ability in comparison to classical asphalt pavements, such as SMA. The measured temperature in the vehicle was lower in comparison to SMA mixture and the initiation of fire was delayed by around 6 minutes. It is critical time in which people can safely evacuate from the dangerous area of fire. Additionally fire trials confirmed superior ability of the porous asphalt to drain the flammable fluids and to dampen the fire. The performed study showed very promising results of SEPOR pavement, which should be further improved to obtain much higher durability. Such high fire dampening properties can make it desirable pavement not only for tunnels, but also for specific industries which are exposed to fires originated from the flammable liquids which can be spilled on the pavement.

Keywords: Tunnel, Pavement, SEPOR, fire prevention

1. Introduction

Tunnels are one of the most difficult object included in the road or rail infrastructure. It is not only difficult from the constructive point of view, but also taking into consideration safety of the user. As we consider safety of the road user, apart of the traffic accident safety, which we consider for the most of the road infrastructure, in tunnels great attention must be put to the fire safety. Polish requirements [1] states fire requirements for following tunnel elements according to the European standard [2]:

a) fire separation elements (main structure, walls, ceilings) – required fire resistance class A2, d0;
b) elements of the facing of the tunnel – required fire resistance class, A2-s1, d0;
c) other non-constructive elements of tunnel – required fire resistance class B or B_{fl}-s1 – in the case of floor/pavement material.

Following classes are similar across the Europe, and for most of the elements, similar materials are used. Another question is what kind of material should be used as a pavement. The question was of high importance after tragic fire in Mont Blanc tunnel in 1999 r., in which 39 people died. Conducted investigation and research stated that the type of used pavement materials did not have any influence n the size and the process of the fire [7,8]. Nevertheless this raised many questions regarding used pavement type and till today there are no unified requirements in this matter.

Apart of the typical pavement solutions, many different types of pavement materials were presented as a solution to improve the fire safety in tunnels. The purpose of this study is the fire safety analysis of the used typical materials for pavements in tunnels and presentation of the first trials of the innovative pavement material solution – SEPOR [20], which improves the performance properties (such as noise) and fire safety properties of the road structure. The paper presents two fire trials conducted for the typical bituminous materials and SEPOR pavement and analyses its potential for usage in tunnel structure.

1.1. Pavement structures used in tunnels

Currently there are no unified requirements regarding material used for pavement in tunnels. While there are some countries which recommend one type of pavement – either cement concrete or asphalt courses, there are some which does not state any specific conditions, apart from the fire resistance class. Among the used bituminous materials, some countries recommend specific mixtures, and in others one can design any type of mixture. Among the most common mixture types following can be listed: asphalt concretes, stone mastic asphalts or permeable mixtures such as porous asphalt. SEPOR mixture presented in this paper can be treated as the permeable mixture.

Cement concrete pavement structures are required in tunnels of length longer than 500 or 1000 meters in following countries: Austria since 2001 [5,7,13], in Slovakia since 2001 [6,7], in Slovenia and Spain since 2006 [5,7] and in Bosna and Hercegovina since 2013.

Asphalt pavements are treated equally with cement concrete pavements in following countries: Poland, Germany [7], Croatia [7], Norway (especially for low volume roads) [9,18], Italy [15], Holland, Denmark, Great Britain [10], Ireland [11], France, United States [16] and Australia [14]. However different countries recommends different types of mixtures for the tunnel pavement. In Czechia [19] recently the law documents required only cement concrete pavements, but last research and construction projects such as Blanka tunnel in Prague showed the possibility of the usage of asphalt pavements. Very often the recommendations from specific countries contradicts each other – for example in treating permeable mixtures.

Innovative solution developed among other applications for usage in tunnels was SEPOR (Safe, Eco-friendly POroelastic Road Surface) mixture. It is low noise poroelastic mixture based on the highly polymer-modified asphalt binder (45/80-80 according to EN Standards with approximately 7.5%

of SBS polymer). Poroelastic Road Surface is a special wearing course for road pavements with very high content of interconnecting voids (to facilitate the passage of air and water), while at the same time the mixture is elastic, due to the use of rubber (or similar products) used as the main aggregate. The desirable air void content is at least 20% by volume and the desirable rubber content is at least 20% by weight. For current research one specific mixture of designation SEPOR-PSMA5 W4 was used. It consists of 0/5 mineral aggregate, 0.5/4 rubber aggregate and 45/80-80 binder.

1.2. Fire issues in tunnels

Most of the technical reports and research projects published by the PIARC organization and European Asphalt Pavement Association EAPA [3] reports that both asphalt and cement based pavement structures can be used in tunnels with no negative impact on fire and traffic safety. According to De Lathauwer [8] research conducted in France indicate, that while toxic fumes are emitted by bituminous pavement during fire, it is negligible amount in comparison to the toxic fumes emitted by burning cars, and the influence of the smoke from pavement is negligible during evacuation of the car passengers. Additional information confirmed during the presented study indicated, that asphalt pavements does not contribute to propagation of the fire and are hard to fire. The temperature required for self-fire in case of asphalt pavements is very high. Depending on the test results the self-fire temperature of asphalt mixtures ranges from 430 to 530°C [4, 23]. Additionally it should be noted that there are numerous additives used in bituminous mixtures in fire risk areas to slow down the temperature, to increase the temperature of self-fire and to dampen the propagation of the fire spreading. Appropriate additives can slow down the ignition of the fire by few or even a dozen of minutes. But it should be noted that numerous research conducted in accordance to the EN 13501-1 standard proved high resistance to the action of fire [23] and are in accordance to national law regulation stated for construction materials in tunnel.

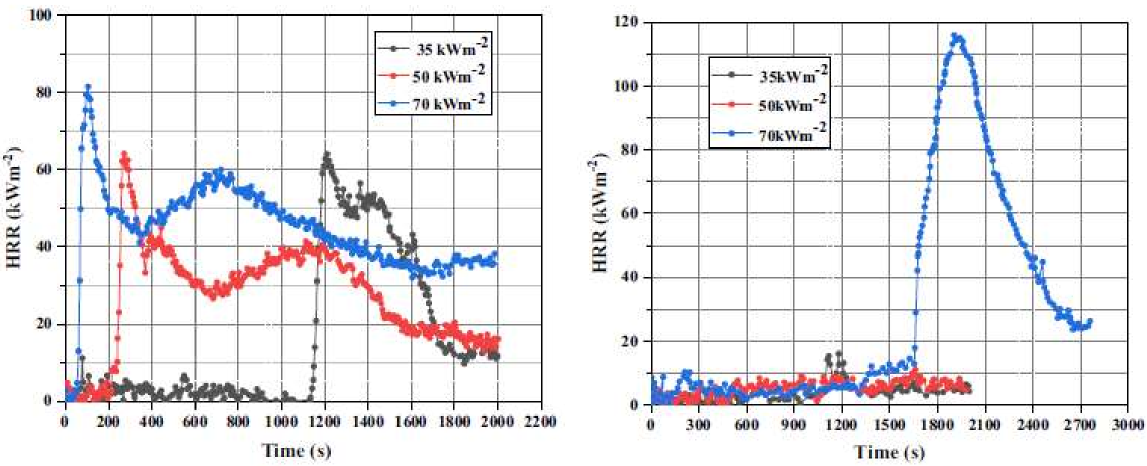
2. The influence of pavement type on fire safety in tunnel

In the case of fire in tunnel the first minutes after the appearance of fire are of a key importance. It is a time, in which people near the source of fire should: leave the car and evacuate or help the people trapped in the car, to safely leave it and leave the area of fire. Due to this critical first minutes the most important issues are: the speed (time) of fire spreading and propagation and the appearance of smoke (and the time in which the smoke appears). If fire is ignited by the vehicle the spread of the flames to the next vehicles is caused usually by reaching very high temperature in the vicinity of the vehicle and its self-ignition (usually firstly the fire ignites in the elements made by plastic or in tires) or by the direct action of fire. Reaching very high temperature needed for self-ignition requires time, usually few minutes from the appearance of flame source. Polish regulations [1] indicates, it is around 3 minutes to reach the temperature of around 900°C. This time can be shortened if easy to fire liquids, such as oils and gasoline are spread on the surface of the pavement. The second cause for fire spreading is direct action of flames. In this case, the time needed for ignition of the near vehicles is much shorter and equal to around dozen of seconds. But direct action of flames are only in the nearest area of the vehicle. In the case of spreading the easy to fire liquids direct flame area is similar to the area of spreading the liquids.

The road pavement of tunnel, constructed from both cement and asphalt concretes, does not set on fire due to the high temperature or direct action of flames. Usually in the case of asphalt mixture during fire firstly the bituminous film on the surface burns. But it should be noted that in typical asphalt concrete, asphalt is only around 5-6 % of mass of the whole mixture. The rest is rock aggregate, which is non flammable material. And the bituminous film on the surface of the layer usually is wiped in the first years of the exploitation of the pavement. Cement concrete is nonflammable material. During burning of the bituminous film some toxic fumes can appear (usually the carbon oxide compounds). But this appears just after reaching the temperature of 500°C, so in advanced phase of fire. Also the most of the toxic fumes are originated from burning objects, such as vehicles. And as stated before, from the point of view of safety and people evacuation, the most important is the first phase of the fire.

Most of the research show, that in the first phase of fire, both types of pavements presents similar fire safety properties. But it should be noted, that in both cases, there are specific properties, which can further increase the fire safety of the tunnel.

One of the most important property which influences the time of fire initiation is void content (see fig 1). With the increase of the mixture porosity, the ability to drain the flammable liquids such as oils or gasoline increases. If proper drainage of the pavement is present, this simple property can strongly slow down the initiation of fire. Due to the drainage of gasoline from the surface of the pavement, the appearance of the direct flames is mostly limited only to the vehicles. The spreading of fire on near cars is slowed, so the evacuation time and chances are increased. Also the amount of smoke and toxic fumes is lowered, due to lack of burning of gasoline. Research conducted in China [22] showed the process of heat releasing from the spilled gasoline on the surface of two different asphalt mixtures – dense graded (fig 1a) and open graded (fig 1b). With the increase of the mixture porosity the amount of released heat decreases strongly and the time to the fire ignition increases.



a) Dense graded asphalt mixture. b) Open graded asphalt mixture.

Figure 1. Heat release rate for different asphalt mixtures [22]

With the increase of the mixture porosity also faster drainage of the gasoline, shorter combustion time and lower surrounding temperature were observed (fig 2). The maximum temperature observed for asphalt mixtures for porosity of 16 to 20% did not exceed 300°C. It is lower temperature than need for self-ignition of the bitumen. It was observed that in this range of porosity the voids in the mixture create the “fuel tank” for spilled gasoline in the lower part of the mixture. In the middle part the barrier from micropores appears, which close the access of the air to the gasoline and its fumes. It can lead to the self-exhaustion of the fire. But on the other hand, it was also showed that when the porosity is to high, the fuel drainage is slower, and the gasoline fumes are not blocked by the micropore barrier, what can lead to the extension of the combustion time. But it should be noted, that even in this case the lower surrounding temperature was observed.

And while this phenomenon seem very promising, there are several shortcomings, especially after the fire, when the gasoline need to be drained from such pavement course. It is one of the reason, why in some countries, such as Australia [23] does not recommend to use porous asphalt in tunnels, even when this mixture is used outside of the tunnel. Research [24] conducted for other bituminous mixtures showed that the surrounding temperature was notes in the similar level as the temperature of self-ignition of the bitumen.

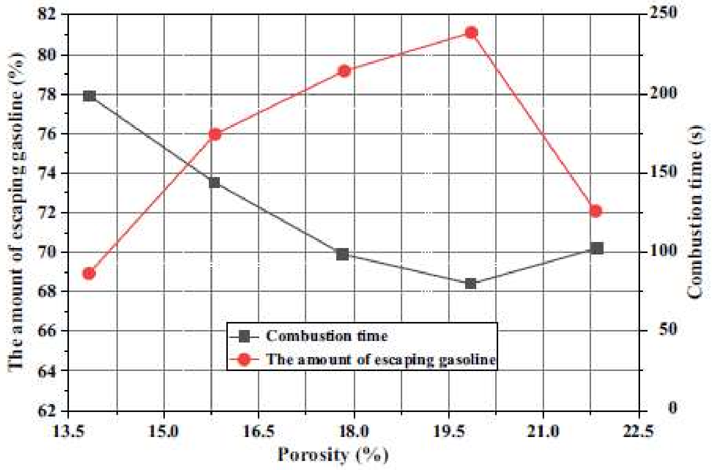


Figure 2. The influence of porosity on the drainage of gasoline and combustion time [22]

The research on the flammability of different types of pavements were conducted also in Poland [20,21] (presented in more details in this paper) and in Czechia [19,23]. In both cases compared where different types of asphalt and cement mixtures. In both research it was observed that more porous mixtures are less prone to fire [19,21,23]. Also the observed surrounding temperatures measured on different heights were lower in the case of porous mixtures in comparison to typical asphalt or cement pavements. The research conducted in Czechia are presented in figure 3 and 4.

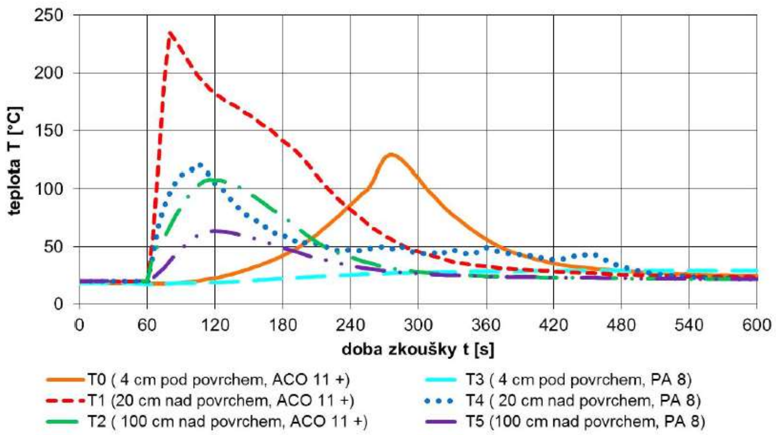


Figure 3. The surrounding temperatures for the 4, 20 and 100 cm above the surface for dense graded asphalt concretes (ACO) and porous mixtures (PA8). [19]

Figure 4 The comparison of the gasoline combustion of the surface of different asphalt mixtures: porous mixture (PA 8), stone mastic asphalt (SMA11, with ~7% of bitumen) and typical asphalt concrete (ACO 11) [23]

In the case of smooth surfaces (with dense structure) such as asphalt concrete, stone mastic asphalt or cement concretes, the surrounding temperature significantly increases just after 60 seconds after appearance of fire. In the case of porous asphalt the fire is dampened due to the drainage and storage of the gasoline. This phenomenon was confirmed by many independent research.

3. Poroelastic pavement - field evaluation of fire resistance and fire slowdown possibilities

One of the most promising technology that could be used in tunnels and is still under research stage is poroelastic pavement [12]. The idea of that pavement as a Poroelastic Road Surface (PERS) consists with wearing course with a very high content of interconnecting voids to facilitate the passage of air and water through it. The surface is elastic due to the use of rubber or other elastic products as a main aggregate. The design air void content is at least 20% by volume and the design rubber content is at least 20% by weight [25]. Poroelastic Road Surfaces have a very interesting and important feature namely they prevent the spread of fire associated with burning spilled fuel. There is because of open structure and elastic properties of that mixture. The idea of PERS pavement as prevention layer in case of burning spilled fuel is presented in Fig. 5.

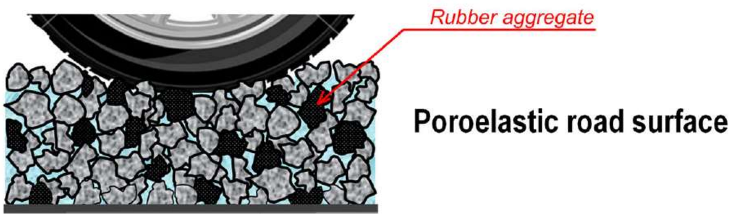


Figure. 5. The idea of PERS pavement also as prevention layer in case of burning spilled fuel

According to Ejsmont et al. [25] comparison of fire development on three different pavements is shown. On each pavement 0.25 liter of gasoline was spilled and after 30 seconds ignited by gunpowder charge. In the Fig. 6 the fire development after 5 and 30 seconds from ignition is presented. On figure 7 the development of temperature for each of the section is presented. It is clearly visible that the trend of the temperature development is lower for all of the tested SEPOR pavements in comparison to classical asphalt and cement mixtures. Additionally the temperature measured on the floor of the vehicle is much lower than measured for the classical pavements.

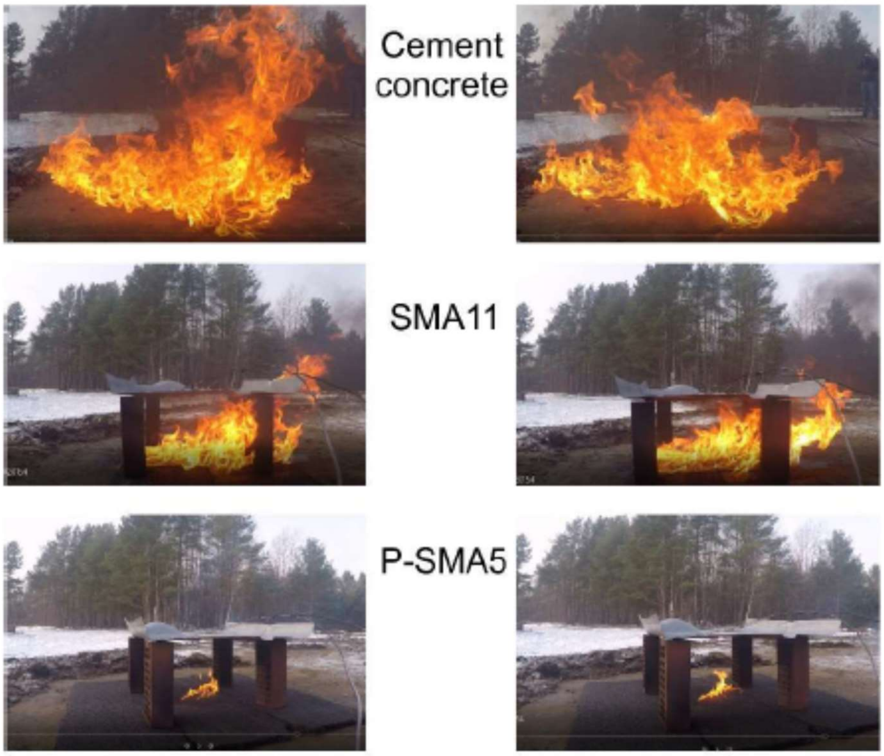


Figure. 6. Flames over three tested road pavements 5 and 10 seconds after ignition [25]

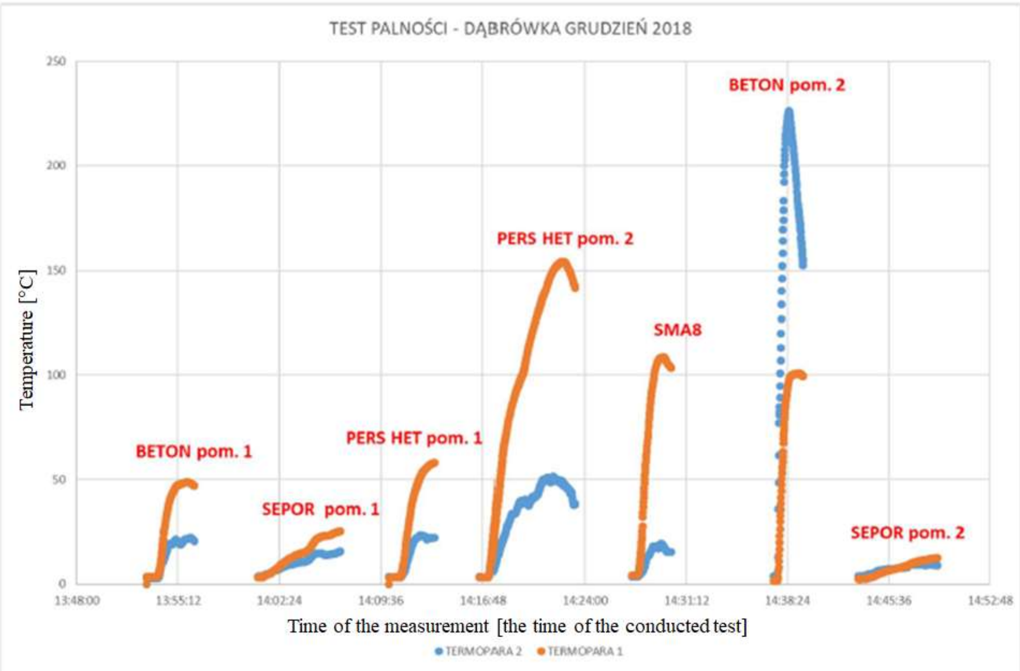


Figure. 7. The measurement of the vehicle floor temperature [25]

Poroelastic pavement P-SMA5 clearly damps flames as gasoline penetrates the material thus making it difficult to contact with oxygen. According to program SEPOR [26, 27] two test sections were built in 2019 to test the production technology and performance of the new poroelastic pavement. It is observed that some of the problems with previous poroelastic materials were mainly eliminated (especially delamination from the base layer and raveling) but noise reduction is a little less than expected (up to 9 dB). Rolling resistance for car tires is acceptable and fire properties (damping of spill fuel fires, toxic gas emission) are very good. The results from those trial sections are showed in Figures 8–10, The main observation was the development of fire in time on different sections. One second after ignition flame under the car standing on drainage asphalt was very small, flames under cars standing on poroelastic pavements were somewhat higher but also not dangerous, while in the case of comparable pavement (SMA8) it would already be dangerous to leave the car. Ten seconds after ignition car standing on SMA8 was already burning with flames as high as 2–3 m making the evacuation of passengers nearly impossible. Unlike SMA8 it would still be possible to leave cars standing on poroelastic pavements, and the flame under the car standing on drainage asphalt was very small and not dangerous. A similar situation was recorded 30 s after the ignition.

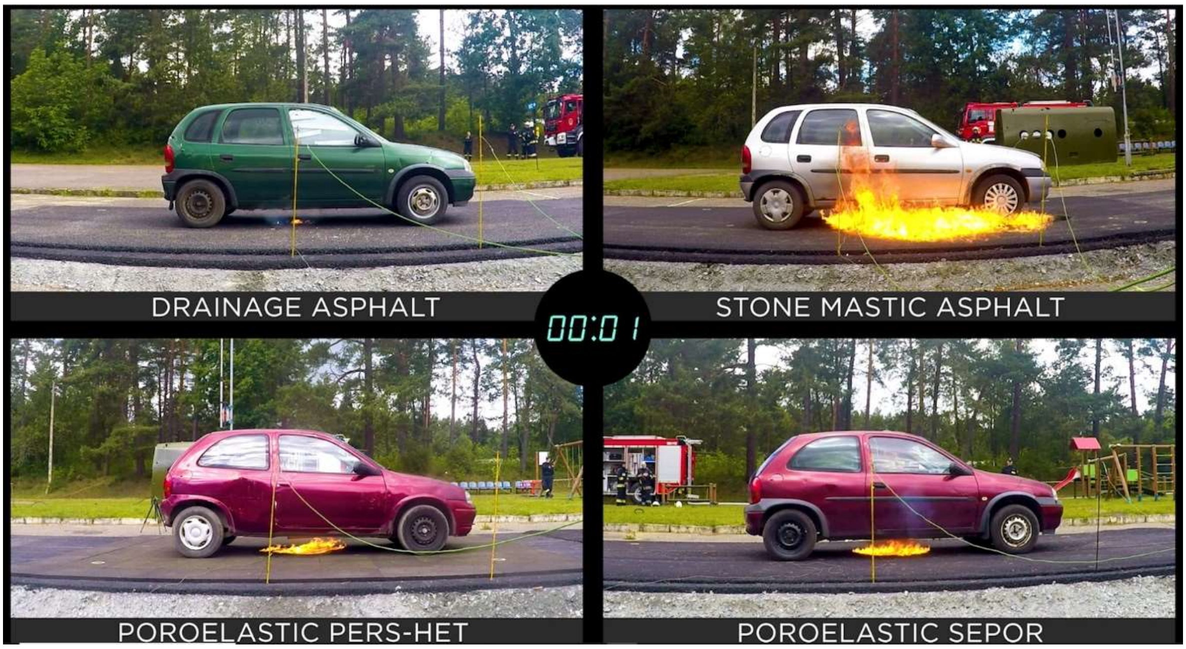


Figure 8. Development of fire 1 s after ignition [27]

Figure 9. Development of fire 10 s after ignition [27]

Figure 10. Development of fire 30 s after ignition [27]

Summarizing the results conducted in the SEPOR program [28, 29, 30], a spill of 20 L gasoline on drainage asphalt burning was not able to ignite the car so after 10 min the experiment was stopped. It is very promising result according to safety in tunnels when time to leave the car is crucial. On poroelastic pavements, it would be possible to leave the car during the first 2 min of fire. After 2, min the interiors of cars started to burn due to heat coming through the floors. In the case of typical dense pavement like SMA8, after only 3 s, the fire cut off the possibility of evacuation through the door, and after 30 s, the interior of the vehicle was on fire. The experiment conducted in program SEPOR shows that drainage pavements have very favorable fire properties and may be used in places where fire risk is very high like tunnels, but also fuel stations, etc. Poroelastic pavements like SEPOR exhibit also very good fire properties despite the high contents of rubber. Regardless of whether modified asphalt or polyurethane is used as the binder, their fire properties are similar. In the Fig. 11 the relationship between time and temperature measured closed to vehicle engine for different types of pavements is presented.

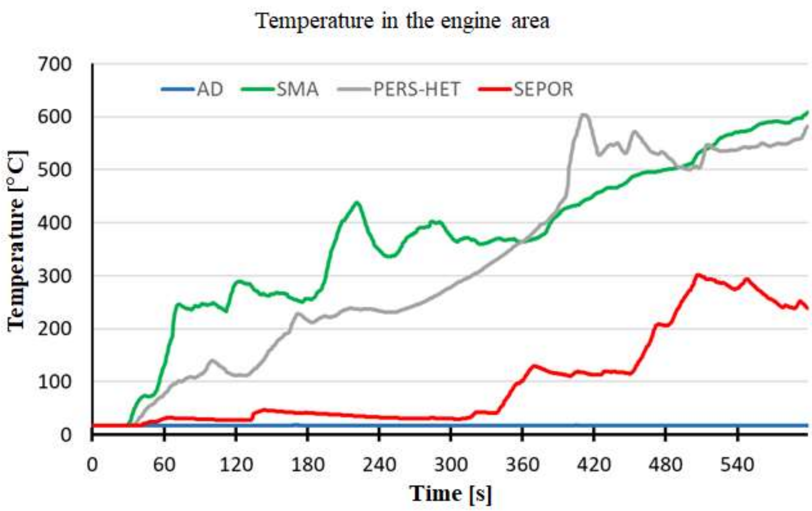


Figure. 11. The relationship between time and temperature for different types of pavements tested in the program SEPOR [28, 29, 30, 31]

I was proved that SEPOR poroelastic pavement obtained the lowest temperatures measured closed to engine and for the longest time period which enables the rescue of passengers from cars stuck in road tunnels during road accident.

4. Conclusions

The paper presented study regarding pavement types used as typical in tunnels and the innovative pavement SEPOR which is still under research, and for which the initial fire loads were performed. For all the presented information following conclusions can be stated:

- Both asphalt and cement pavements presents similar fire protection performances in the first phase of the fire. In the second phase the concrete pavements presents better performance.
- For the specific range of voids in the bituminous pavement (16-20%) isolated “gasoline storage” is created in the bottom of the porous layer. Porous pavements also shows better drainage of the spilled flammable liquids. This was confirmed by various independent studies conducted in many countries.
- Innovative pavement SEPOR presents much better performance in regards to fire protection in comparison to typical asphalt pavements. It joins the advantages of porous pavement with appropriately designed materials.
- Poroelastic SEPOR pavement showed dampening of the flames in the first phase of fire and decrease the temperature which appears in the vehicle floor.
- Field test on the real vehicles showed that the usage of the poroelastic SEPOR pavement can prolong the ignition of the fuel and start of the fire by even 5 minutes in comparison to classical asphalt and cement concretes. To prove this better performance similar test should be conducted in the closed environment which simulates the tunnel environment.

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