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Risks related to car fire on innovative Poroelastic Road Surfaces - PERS.

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ABSTRACT

In order to reduce tyre/road noise the concept of poroelastic road surfaces (PERS) was invented. PERS is a road surface material that is porous and at the same time it is flexible due to the substantial amount of rubber granulate content (from 20% to 85%). The rubber and stone particles are bound by polyurethane resin instead of bitumen. It was feared that in case of fire, due to high content of rubber and polyurethane, there may be considerable emission of potentially hazardous substances (such as hydrogen cyanide HCN) from burning PERS. Tests performed by the Technical University of Gdansk show that the emission of toxic gases is rather small and that the surface does not promote car fire, even when soaked with fuel. Car fire with fuel spill on PERS surface is less dangerous for passengers than car fire on dense road surface as the fire is spreading much slower. The article presents results of laboratory and road experiments carried out within FP7 "PERSUADE".

KEY WORDS: car fire; PERS; HCN; poroelastic road surface; experimental study

1. INTRODUCTION

The first and simplest roads had a surface of just compacted soil, sometimes reinforced with stones or gravel. The Romans systematically paved their main roads with large and flat stones of irregular shape [1]. Since ancient times, many new materials were introduced to road building, especially during 20th Century, when horse driven lorries and coaches were replaced by motorized road vehicles. At present, two different types of road surfaces are in common use: ***concrete surfaces*** and ***surface dressings***. In concrete surfaces mix of stones and sand is bound together with binder (usually bitumen or Portland cement). When bitumen is used, the surface is considered ***flexible*** and when cement is used, it is considered ***rigid***. Surface dressing is a very different type of surface, as the underlying surface (the base) is sprayed with glue and then covered with a layer of stone chippings. Even flexible, bituminous road surfaces are not elastic as their deformations are generally not reversible.

The surface that lets no water through it is called a ***dense*** surface, while a surface that lets water penetrate at least the upper layer is called ***porous***. The concept of ***poroelastic*** road surface was invented in Sweden more than 30 years ago. Poroelastic road surface (PERS) is a surface that has accessible voids (it is porous) and at the same time it is flexible, so it deflects considerably when loaded by tyre and when the pressure diminishes it comes back to its original shape (elastic behaviour instead of plastic). Different types of road surfaces used for top layers of modern roads are shown in Figure 1.

1.1 How Poroelastic Road Surface is Constructed

PERS is manufactured in a similar way like porous asphalt concrete but the mixture contains a large percentage of rubber particles as well as hard aggregate (stone and sand). It is bound with polyurethane instead of bitumen. The voids content after the marginal compaction during the laying process is around 30%. The structure of three different poroelastic materials which were tested at the Technical University of Gdansk (TUG) is shown in Figure 2. The PERS material shown in the middle of Figure 2 has no mineral aggregate and contains only rubber particles and polyurethane. This material was used ten years ago for tyre/road noise testing, but due to its low skid resistance this concept was abandoned. For all fire tests reported in this article, the PERS material shown on the left hand side of Figure 2 was used. The surface is designated as PERS-ARNAKKE and contains mineral aggregate, rubber granules and one component polyurethane resin. It has narrow pores as the aggregate is approximately 2 to 5 mm in size. The material is described in [6].

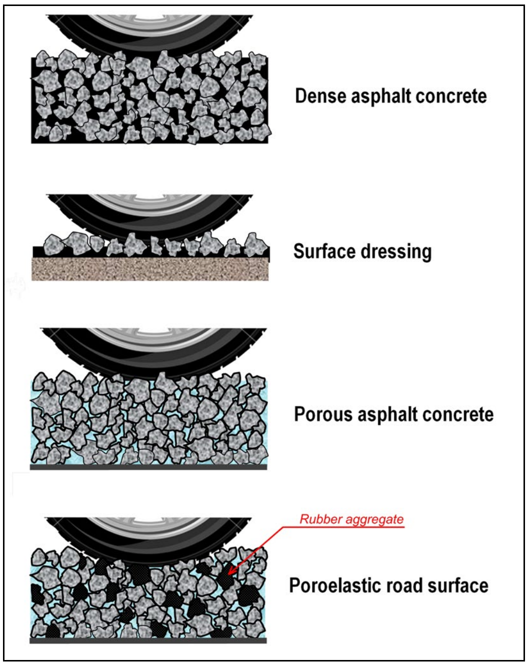

Figure 1. Schematic description of different types of road surfaces: dense asphalt concrete, surface dressing, porous asphalt concrete and PERS

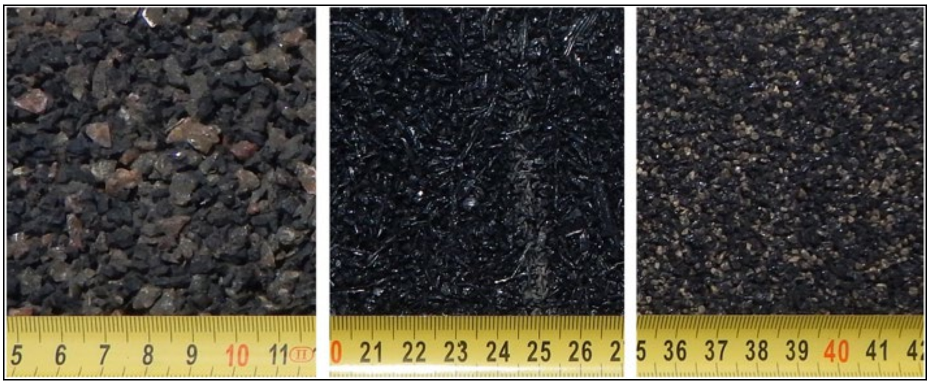

Figure 2. PERS materials tested at TUG - from the left: PERS-ARNAKKE manufactured by VTI, Sweden; PERS without mineral aggregate manufactured in Japan; PERS-HET manufactured by HET, Germany

1.2 Why to use Poroelastic Road Surfaces

The primary reason for the development of PERS is to reduce tyre/road noise that is the dominant noise source for most car and truck driving conditions. The porous structure of PERS reduces noise generated by aerodynamically related mechanisms, while elasticity reduces vibration related mechanisms. Altogether, according to the laboratory and road tests, PERS may reduce vehicle noise by 8-10 dB in relation to typical road surfaces used nowadays, for example Stone Mastic Asphalt SMA12. What is more, poroelastic road surfaces should be more durable when studded tires are used. As a considerable amount of rubber aggregate is used for PERS mixes, the problem of recycling waste tyres may be solved at the same time.

1.3 Problems that may be related to the use of PERS

Besides many technical problems at the developing stage of PERS (as for example ravelling), the major concern of road decision makers that has to be addressed is possibility of excessive danger in the case of an accidental car fire on poroelastic road surface containing rubber particles and polyurethane. The risk of the emission of hazardous substances (such as hydrogen cyanide HCN and mono-nitrogen oxides NOx) has to be assessed and controlled. It was also speculated that the porous structure of PERS would promote violent combustion when soaked with fuel, thus reducing chances of passengers to escape from burning vehicle. The last concern was in clear contradiction to findings of Meiarashi [2] who already fifteen years ago established by burning 5 x 5 meter sample of PERS that regarding spreading speed and flame height, the PERS was safer than the dense asphalt concrete. In his investigation, Meiarashi used PERS without mineral aggregate and diesel oil as a fuel. He has not burned a whole car on PERS material however.

As safety is a principal issue for the PERSUADE consortium, the project management decided to perform comprehensive fire tests of PERS samples. This task was given to the Technical University of Gdansk, Poland and the results are presented in this article. The article covers only emission of HCN, CO and subjective evaluation of the fire spread. During the tests NOx was not monitored as it was judged to be less dangerous for car passengers subjected to the fumes only for a very short period. What is more, combustion of the spilled fuel on the PERS surface was far less vigorous than on cement concrete, thus temperatures were lower so overall NOx emission should also be reduced.

2. LABORATORY EXPERIMENTS

2.1 Thermal stability of PERS

First experiments were performed at the laboratory on 30 g samples of PERS. The material was placed in a glass container of 1100 cm^3 volume and tightly closed with a Teflon stopper with built-in silicon membrane. The glass container was then placed in a thermostat that was gradually heated to a temperature of 200°C (heating time was 30 min). At the end of the heating cycle, the glass container was cooled to ambient temperature, and 20 cm^3 of a gaseous phase was sampled on a sorption tube filled with Tenax TA sorbent, where the analytes were quantitatively retained [3]. However, it should be observed, that cooling of the glass container may have decreased concentration of HCN to some extent, so the quantitative results should be treated only as a rough estimation.

Qualitative analysis of the organic compounds released from the test material was performed by using a thermal desorption technique (TD) liberating organic compounds from the sorbent bed Tenax TA, and gas chromatography (GC) coupled with a mass spectrometer detector (MSD) to separate and identify the eluting organic compounds. The results of the tests are presented in the form of the chromatogram (see Figure 3) and as an identification report drawn up by comparing the obtained mass spectra of compounds present in the analysed sample with the spectra of *2-isocyanato-2-methyl propane* from the NIST reference library (See Figure 4).

For the quantitative analysis the sample was prepared in the same manner as described above. Quantitative analysis of compounds released from the test material was performed by using a thermal desorption (TD) and gas chromatography (GC) coupled with flame-ionization detection (FID). Concentrations determined as an average of the two independent measurements are: *2-isocyanato-2-methyl propane* - 8 mg/kg PERS, all organic compounds (as a toluene equivalent) - 15.4 mg/kg PERS.

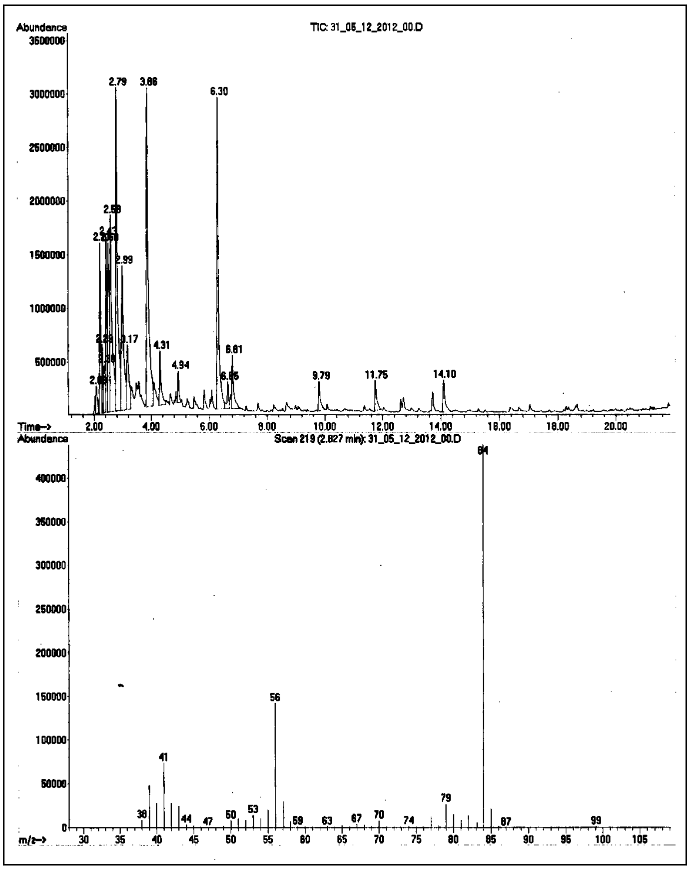

Figure 3. Chromatogram of fumes collected during thermal decomposition of PERS. Mass spectrum shown in lower diagram was obtained for retention time 2.8 min.

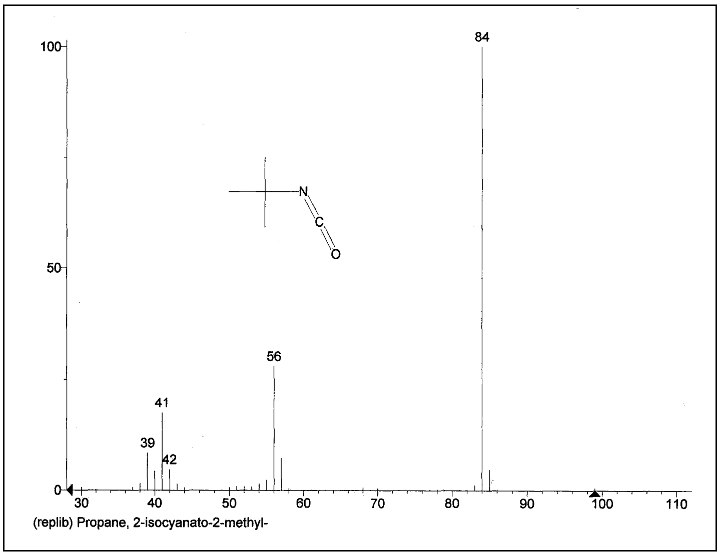

Figure 4. Reference chromatogram of 2-isocyanato-2-methyl propane

In order to estimate HCN emissions during a fire, several tests were performed at the TUG in conditions not covered by any standard but judged as equivalent to a real car fire. To burn the samples, a barbecue cooking grill was used with a cylindrical hood made of stainless steel supported over the grill. The upper part of the hood was closed by a Teflon stopper. Samples of PERS weighing approximately 40 g and soaked with kerosene were placed on the grill, covered with the hood and ignited. The fumes were sucked through a particles filter filled with silane treated glass wool and two scrubbers filled with a 0.1 mol/l solution of NaOH. The scrubbers were used to collect gaseous product of PERS combustion such as the cyanide ions. The samples were collected starting from the ignition of PERS material until the disappearance of the flames. The test setup is shown in Figure 5.

Determination of the quantity of HCN formed during PERS material combustion was performed by using the Spectroquant® cyanide test. The Spectroquant® method is compatible with EPA 335.2 and ISO 6703 standards. The results of the tests are presented in Table 1. The mass loss of samples and emissions of HCN were calculated with regard to the initial mass of samples. It must be stressed, that the results of burning experiments depend very much on burning conditions that fluctuate considerably if the sample is soaked with kerosene and ignited. Nevertheless, the authors judged that standard procedures, where the sample is subjected to constant temperature in a quartz tube are less representative of a car fire in the open space. The only way to burn PERS during a car accident is to soak it with fuel and to ignite it. The tests done at the TUG reproduced such conditions.

Table 1. Results of laboratory fire tests performed at TUG

Sample No	**Initial mass of the sample [g]**	**Relative mass loss of the sample [%]**	**Relative emission of HCN [mg/g]**
PERS1	29	9	0.0082
PERS2	39	9	0.0065
PERS3	40	10	0.0051
Average			**0.0066**

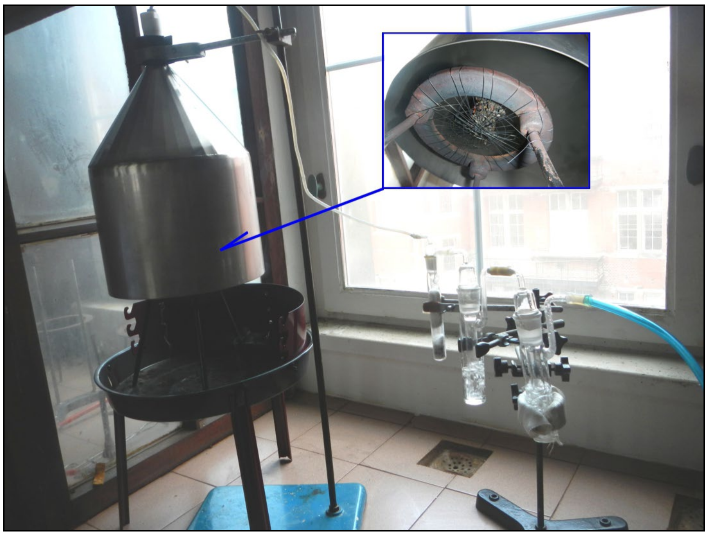

Figure 5. Test set-up used at the Technical University of Gdansk

To estimate HCN, CO and CO_2 emission during the burning process with controlled amount of air supply, some additional tests were performed. The burning of the test samples was performed according to the standard PN-88 B-02855 in DIN Furnace with an airflow of 100 dm^3/h at temperatures 450°C, 550°C and 750°C. For each PERS sample that was burned in the furnace the fumes were collected in two absorber tubes filled with 200 ml of 0.1 mol/l NaOH. Table 2 summarizes results of CO and CO_2 measurements as well as HCN and $(CN)_2$ performed according to EN ISO 14403 standard. The emission values were calculated with regard to the initial mass of samples. There is a clear indication of strong temperature influence on emissions.

Table 2. Relative emission of CO and CO_2 during tests performed in DIN Furnace

Sample temperature [°C]	**Sample No**	**CO emission [mg/g]**	**CO_2 emission [mg/g]**	**CN emission [mg/g]**
450	1	17	9	
	2	10	16	
	Averaged	**13**	**12**	**0.007**
550	1	42	95	
	2	40	54	
	Averaged	**41**	**75**	**0.260**
750	1	54	460	
	2	77	820	
	Averaged	**66**	**643**	**0.950**

Comparison of results obtained by burning PERS soaked with kerosene with the results of tests performed in a DIN Furnace shows, that burning PERS in the open air results in much less emission of HCN than burning PERS in DIN Furnace at very high temperature with controlled (restricted) air flow. According to Tsuchiya [4], many factors can influence the emission of HCN during a fire. The most important, however, are the temperature and oxidizing capabilities of the atmosphere. The effect of oxygen usually increases the temperature of the fire and leads to an increased HCN production. On the other hand, according to Simonson et al. [5], higher temperature and flaming decrease the emission to the environment by "burning" (oxidizing) HCN if there is sufficient oxygen in the mixture.

3. MEDIUM SCALE FIRE EXPERIMENT

After the laboratory tests reported in section 2 it was decided to perform Medium Scale outdoor tests to measure HCN concentrations in the air at the fire zone. The PERS samples were placed on a cement concrete surface. Sample A was manufactured in a conventional way, whereas in sample B the aggregate was pre-coated with Novolac® (phenol formaldehyde resin used to pre coat the aggregate to increase bonding strength between the aggregate and the polyurethane). Each sample was soaked with 2.5 litres of 95-octane gasoline and ignited by pyrotechnic fuses and small charges of gunpowder. The burning process was observed and HCN concentrations in the air in the vicinity of the burning sample were measured.

Each time the fire was started, the HCN concentration in different locations close to the burning sample was measured using test instrument ToxiRAE described in the section 4.1. The measurements were carried out at the distance range of 0.3 - 5 m from the centre of the fire. These medium scale experiment showed that:

1. It is not easy to ignite a PERS surface soaked with gasoline. Of course, it is fairly easy to ignite gasoline but it burns only on the outer surface of PERS and the material is infiltrated by flames very slowly. Despite using gunpowder to increase the temperature and placing cotton wool soaked in gasoline on the sample, the PERS fire was not vigorous anyway - see Fig. 6. Even after 3 minutes, the fire was confined to the gasoline soaked area, concentrating on the path where cotton wool was still burning - see Figure 7.

2. A spill of 2.5 l of gasoline resulted in a burning path of less than 0.25 m^2. The fire has not propagated over the surface. Burning area was a kind of "point" fire source of more or less constant size.

3. The HCN concentration in the air at the distance of 2-5 m from the source was max 1 ppm. At very close range (0.3 - 1.0 m) the concentration was only for a very short moment as high as 25 ppm (when the sensor was fully covered with black smoke emitted from the fire for a short period when one of the burning PERS plates was turned upside-down to facilitate combustion). For the rest of the time the HCN concentration at that short distance was 2 - 5 ppm.

4. The PERS fire was very easy to extinguish with a small amount of water when the gasoline spill was burned away, without any adverse effects on the HCN concentration.

5. The sample B of the new PERS material (aggregate covered with Novolac®) has shown very similar results of HCN concentration to the "standard" sample A.

After the “medium scale” experiment it was decided to burn a passenger car on the PERS material in order to obtain the data concerning emissions and flame propagation as realistically as possible.

Figure 6. Fire of PERS material 30 seconds after ignition of 2.5 litre of gasoline (strong wind from right side). Heights of the flames is 20 - 30 cm. Cotton wool visible on the right is responsible for most of the flames.

Figure 7. Fire of PERS material 180 seconds after ignition of 2.5 litre of gasoline - mostly cotton wool is burning

4. FULL SCALE FIRE EXPERIMENTS

After the laboratory tests and the “medium scale” outdoor tests reported above, a third fire test of poroelastic road surface was conducted with a full scale car fire. The test was performed on 9th May 2013 on the yard of GRYF Bus Company in Zukowo, Poland. The meteorological conditions on the test site were as follows: air temperature 27-28°C, light wind 1-3 m/s (changing direction), humidity 52% and a dry base layer.

4.1 Instrumentation and test object

To evaluate the concentration of HCN during tests a portable Personal Gas Monitor ToxiRAE II with HCN sensor was used [3]. The ToxiRAE II is a single-gas monitor providing continuous, digital display of the gas concentration, STEL, TWA and peak values, as well as high, low, TWA and STEL alarms. The measuring range of this instrument is 0 - 100 ppm with a resolution of 1 ppm. The instrument was two-point calibrated (auto-zero at start-up, and 20 ppm span/standard reference gas before the measuring campaign).

A car Peugeot 306 XR was used as a burning object placed on the PERS (see Figure 8). The fuel was drained from the car tank and the tank was removed in order to avoid an explosion. All the other fluids were preserved. In addition, air-bags were left in the car.

During the experiment, a PERS-ARNAKKE sample manufactured by VTI in Sweden was used. The PERS used for this experiment had narrow pores as the aggregate was approximately 2 to 5 mm in size. The material is described in [6].

Figure 8. Full scale Fire Test setup

4.2 Execution of the full scale fire experiment on PERS

The PERS plates were laid on a dry cement concrete surface. The car was placed in the middle of the PERS surface and an ignition system was placed under the car floor. Observation points were marked around the car at a distance of 5 m from the car centre - see Figure 9. The measuring instrument was moved from location to location with 15 s interval. When the ignition system was checked, the PERS sample under the car was soaked with 20 l of gasoline. Most of the gasoline was retained in PERS but after a few seconds some of the fuel (probably 2-5 l) drained in the direction of the car's rear and right side from the PERS layer on the concrete floor.

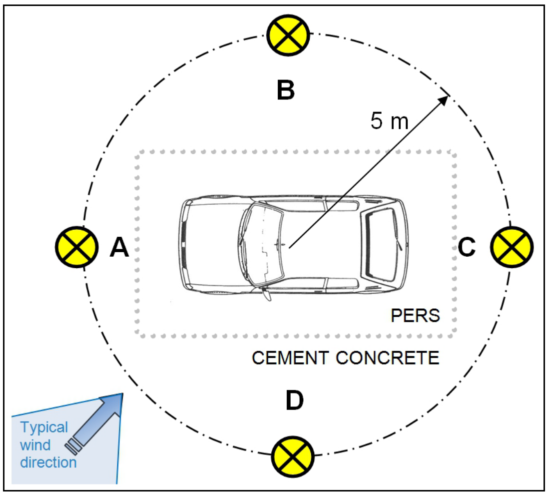

Figure 9. Location of HCN sensors during full scale experiment

For 10-15 seconds after ignition the flames under the car were hardly visible. There was no violent combustion despite 20 litres of fuel spilled under the car. After about 20 seconds the flames on the PERS surface were still very small but the gasoline that leaked from PERS onto the dense concrete at the rear of the car ignited - see Figure 10. The PERS was hardly burning and it would not obstruct passengers to safely escape the vehicle.

At about 90 seconds after the ignition the fuel spill on the concrete on the right side of the car started to burn as well. The fuel on the dense concrete was burning violently and increased the temperature to such a level that the plastic elements on the right part of the car body started to melt and finally started to burn. According to the observers, if the PERS section were larger, there would be no flow-outs of the fuel on the dense surface and, probably, the car would not catch fire at all.

When the plastic parts of the mudguards and bumper started to burn, the flames entered the car interior and progressed from the rear to the front. At about 12-15 minutes from the ignition, most of the PERS surface was burning but the flames were not as violent as the flames in the car interior. After 20 minutes it was decided to end the experiment and the fire was extinguished by a fire brigade. To extinguish the burning PERS surface proved to be a very easy task. A moderate amount of water spray was sufficient. The porous structure helped to keep water inside the material so cooling and isolating effect was enhanced. What is more, the stone particles included in the PERS mix, when rubber and polyurethane are burned, cover the surface with a kind of isolating layer that damps flames and restricts oxygen supply. When the car cooled down, it was properly recycled and returned to a breakers yard.

Figure 10. Car fire on PERS at about 30 seconds after ignition

4.3 Execution of experiment on dense cement concrete

To compare burning characteristics of gasoline on PERS with burning characteristics on dense concrete an additional experiment was performed. 20 litre of gasoline was poured on the dry, dense concrete and ignited. In contrast to the fuel fire on PERS the fire started very violently and after 2-3 seconds all the gasoline was in flames - see Figure 11. It is anticipated that people without protection would be unable to escape from the car in such conditions or would be severely injured (burnt skin and lungs). After 70 seconds from the ignition, all 20 litre of gasoline were burned completely.

One may argue that conditions during the car fire on PERS and the plain fire of gasoline on the dense concrete were different and that the presence of the car influenced the burning process of PERS, for example by restricting oxygen supply. In the opinion of the authors who have witnessed numerous car fires on dense surfaces it is however not the case. A considerable area of gasoline-soaked PERS was not screened by the vehicle body and it did not burn violently like the fuel leaking on dense concrete. Furthermore, the fire built-up process (it is very difficult to ignite PERS with gasoline in it) was exactly the same as during the "medium scale" experiment, where the PERS sample was not screened by anything.

Similar observations were made by S. Meiarashi [2] who concluded that : "*...regarding spreading speed and flame height, the PERS was safer than the dense asphalt concrete*."

Figure 11. Fire of gasoline spill on the concrete surface (10 seconds after ignition)

4.4 Concentration of HCN during the car fire on PERS

During the car fire on PERS the concentration of HCN was monitored at the observation points described in Section 4.2. The results of the measurements performed in front of the car and on its right side are presented in Figure 12 and Figure 13. The photos are related to the observation points and time duration, so it is easy to compare HCN concentrations with the fire character and intensity.

During the measurements the wind direction was changing. Typically, the wind was blowing from the front of the car or from its left side. Most measurements showed the concentrations of HCN between 0 and 4 ppm. During the period of 3 minutes from the beginning of the car fire, which is of utmost importance for survival, HCN concentration was below 1 ppm. The highest concentration of 11 ppm was measured 15 minutes after the ignition at the observation point located at the right side of the car. At that moment the whole car was burning and there was strong wind blowing from the left side of the car.

As it was indicated in [3], a concentration of HCN of 10 ppm (11 mg/m^3) is tolerable for a period of 30 minutes without any irreversible or other serious and long-lasting effects or impaired ability to escape. The same study predicted that in the "worst case scenario" a concentration of HCN during a car fire on PERS surface might reach 10 mg/m^3. This maximal value, as well as predicted "typical" values of 1 mg/m^3 during PERS fire on the road correspond remarkably well with the measurements performed within this experiment.

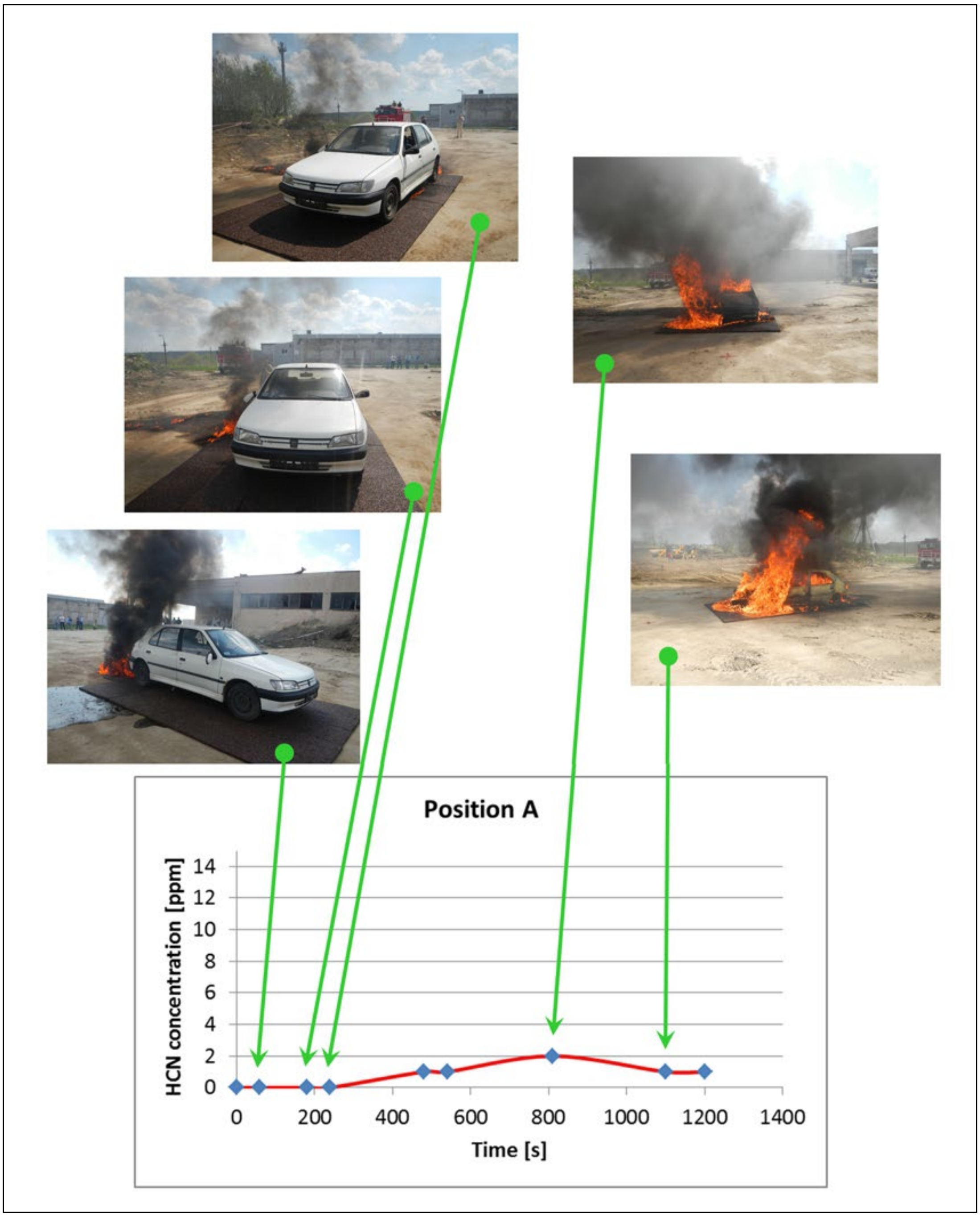

Figure 12. HCN concentrations in observation point located at the front of the car

5. CONCLUSIONS

It must be stressed, that during measurements performed according to the existing standards, the samples are heated to moderate and high temperatures (450, 550 and 750°C in case of PN-88 B-2855) and the airflow is not very strong. On the other hand, during car fires in open space, the temperature of flames is higher (up to 1100°C), and there is an abundance of oxygen promoting oxidation. Big car fires, that are capable to ignite, a rather difficult to burn PERS surface, must produce very turbulent flame-flows so the HCN molecules that are formed in a burning road surface are subjected to high temperatures and flames for a considerably long time. A burning PERS surface that is cooled by the cold road underlayer and fuel evaporation has a fairly low temperature (and this restricts HCN emission), while the emitted HCN is sucked by the air flow to much hotter regions of the fire and this process helps to burn HCN efficiently. Therefore in most cases, during car fires, concentration of HCN will be much lower than the concentration calculated on the base of results presented in Table 2. Equivalence ratio for burning PERS surface in real life ("on the open road") fires is much lower than during experiments performed in the tube furnace, and this leads to lower HCN yields [7].

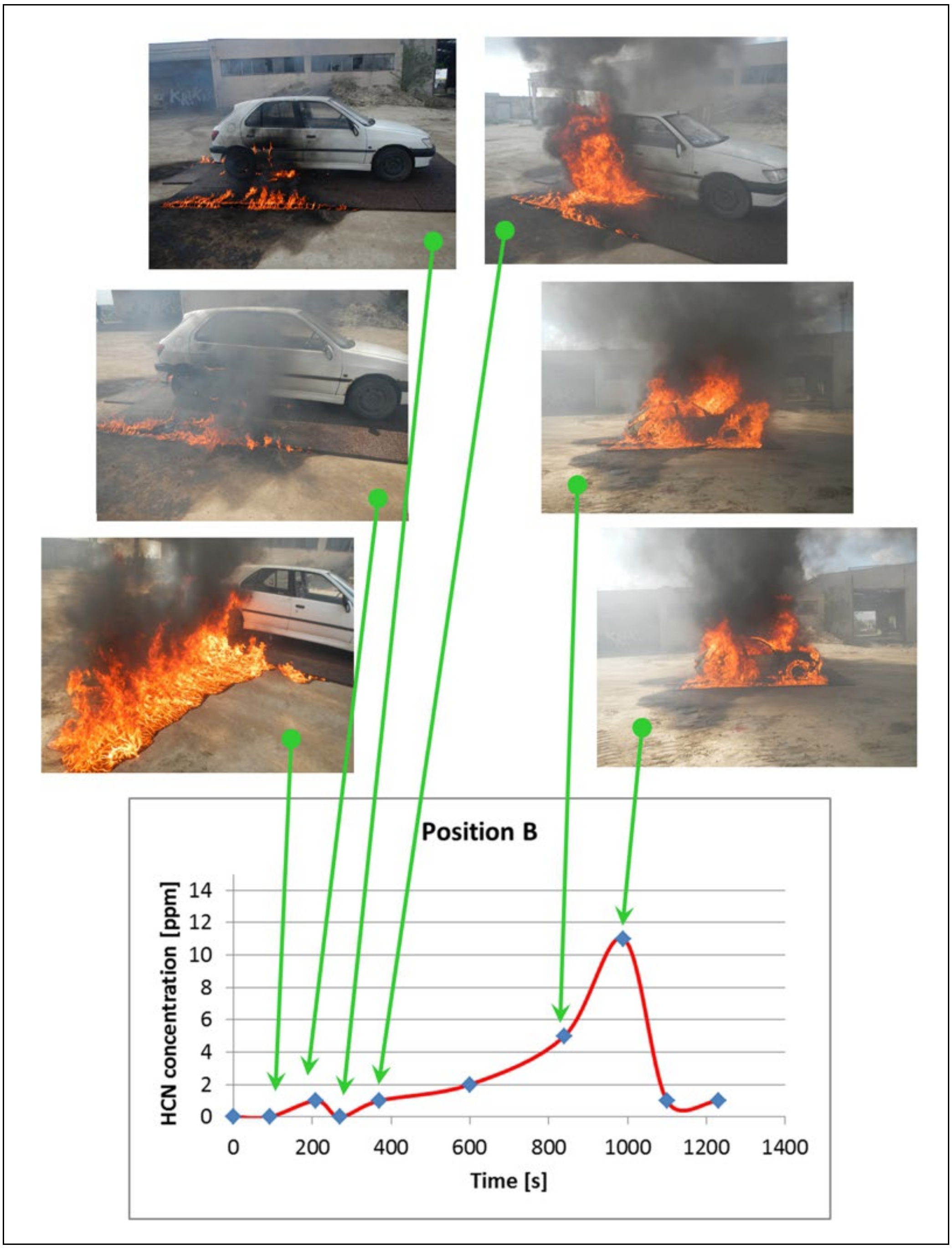

Figure 13. HCN concentrations in observation point located on the right side of the car

In the literature, all the available reports about causalities related to burning plastics, including polyurethane, deal with so called “room fires” or “confined space fires” [8,9,10,11]. In such fires, the concentration of HCN may be very high. In some cases, burning a pillow or a mattress filled with polyurethane foam in a small room may lead to the casualties. The reasons are twofold. First of all, lack of oxygen during a fire in confined space with poor ventilation promotes thermal decomposition of nitrogen containing plastic materials leading to high emission of HCN and CO. At the same time, the produced amount of toxic substance is diluted in only a small volume of air resulting in high HCN and CO concentrations. On the other hand, free space (or well ventilated) fires promote oxidation of HCN and CO as well as lead to very substantial dilution of toxic gases that results in low concentration of HCN and CO.

PERS surface is not easy to ignite. It must be soaked with fuel to start burning. When fuel is burned, the PERS material has self-extinguishing properties, especially when laid on the road with cooling effect from the ground. Tests indicate that during burning the temperature of PERS is in range of 300 - 500 °C.

On the base of experiments, the authors propose to use the following emission values for PERS material similar to the one called "ARNAKKE Mix":

1. Highest emission for decomposition of the PERS in laboratory experiment with low oxygen supply at the temperature of 750°C is 0.95 mg/g.
2. Realistic emission during a car fire, when HCN is after-burned in flames is in range 0.005 - 0.008 mg/g [3].

Results obtained during the full scale fire experiment indicate that there is no risk related to poisoning by HCN produced at the burning processes of PERS and plastic elements of the car in the open space. What is more, PERS surface suppresses fire of spilled fuel for several minutes. The fuel soaks into the porous surface and most of it is not burning due to the lack of contact with oxygen. In addition, the coverage of the burning fuel (size of the spill) is smaller than in the case of a dense surface. The passengers of a vehicle that has ruptured fuel tank during an accident will have much better chances to survive if the car stops on PERS than in the situation when the road surface under the car is dense.

After performing the pilot study described in this article the authors were surprised to find out that the results of tests indicate that PERS **possibly** may be used (or even recommended for use) in high fire risk areas (for example tunnels and gas stations), as it prevents rapid fire spread and it is easy to extinguish, even with water. However, **more experiments should be performed** to investigate behaviour of PERS during "confined space fire" that may lead to much higher concentration of HCN than measured in the open space.

6. ACKNOWLEDGEMENTS

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