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Emission Measurements in the Laboratory and in the Field

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Hot-Recycling of Tar-Containing Asphalt Pavements

Emission Measurements in the Laboratory and in the Field

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ABSTRACT
Hot recycling in pavement construction leads to the emission of hazardous compounds when tar-containing recycled asphalt pavement (RAP) is used. This is due to the relatively high content of substances such as phenols and polycyclic aromatic hydrocarbons (PAH) in tar. The latter are of special interest, because some PAHs have carcinogenic and/or mutagenic properties. High tar content in combination with high pavement temperatures during construction increases the potential health risk for workmen. Switzerland does not currently consider a complete ban of RAP in hot recycling for economical and ecological reasons. Since RAP might always contain some tar, there is a need to fix a scientifically sound limit for the maximum tar content. However, scientific data on the emissions of PAH, as well as the resulting occupational health risk are rare, which motivated the present research. In the laboratory, several parameters, such as temperature, PAH content and viscosity, were varied in an experimental setup to quantify their effect on the resulting emissions. It was shown that temperature is the major factor determining the emissions in the 140 to 240°C range. A PAH content of up to 20000 ppm EPA-PAH in RAP had no significant effect on total particulate matter (TPM) emissions. However, emissions of PAH in the fumes increased proportionally with the PAH concentration in the RAP. Three field tests were carried out with RAP containing up to 5600 ppm EPA-PAH. Occupational health data for the workmen were collected with personal samplers. TPM concentrations were between 2-4 mg/m³, close to the occupational health limit value for bitumen fumes (10 mg/m³). Concentrations of Benzo(a)pyrene (BaP), which is often used as a lead compound, were in all cases below the occupational health limit value of 2 µg/m³ by at least a factor of three. This study indicates that the current Swiss recommended maximum value of 5000 ppm for EPA-PAH in the binder of RAP may be considered as adequate. However, conditions in the field trials did not include a worst-case scenario and the margin to occupational health limit values is small.

KEYWORDS: Recycling, Tar, PAH, Emission, RAP, Field Studies.
1. Introduction

Switzerland has a long tradition of asphalt recycling and introduced in 1993 standards on recycling materials, including recycled asphalt pavement (RAP). These standards describe the allowed application field for recycled materials and the corresponding specifications on material composition and purity (SN 670’142, 1998; SN 670’062 1998). Requirements on the use of RAP were motivated by the conviction that only material with a declared and monitored quality would be widely approved and overcome the image of waste material. This concept has been very successful, and recycled construction materials are well accepted and used throughout Switzerland.

Already the first version of the standard on RAP treated some aspects of possible environmental impacts coming from tar-containing material. Tar contains large amounts of polycyclic aromatic hydrocarbons (PAHs), and in some old road pavements, tar products reach up to 20% (m/m). Various animal experiments and epidemiological studies demonstrate that some PAHs have strong carcinogenic and/or mutagenic properties (European Commission, 2002; IARC, 1985; IARC, 1987). The general awareness is especially pronounced with respect to the carcinogenic and mutagenic potential of Benzo(a)pyrene. Even if the major PAH fraction in tar consists of less toxic compounds such as Naphthalene, the overall toxicity of tar remains a serious issue. The potential health hazard on pavement workers was disputed for a long time in the road construction business. Furthermore, tar containing asphalt has good mechanical properties, which led to its wide use until 1990 in some parts of Switzerland. As a result, tar is present in contemporary RAP in varying quantities. It should be noted that bitumen, which has replaced tar as a binder, contains only traces of PAH in concentrations between 20 and 100 mg/kg, depending on the refinery process.

In the early nineties, when the first recycling standards were written, analytical chemical methods for the quantitative analysis of the toxic PAHs were tedious and expensive. Therefore RAP was divided into three classes: RAP without tar, RAP with small amounts of tar and RAP with large amounts of tar. On first sight this makes sense, as originally binders were categorised by Swiss standards into tar, bitumen-tar, tar-bitumen and bitumen with defined tar contents. However, for several reasons this concept did not work properly:

– Road layers are typically milled without considering the individual pavement layers as, in general, no information about the type of binders used in the different layers is available.

– In most recycling plants, low and high-contaminated RAP is stored together on one heap.

– Nowadays, some pavements have already been recycled for the second or even the third time. Because RAP was originally added only in proportions of about 10 - 25 %, tar in the recycled layers was gradually diluted, resulting in pavement material with a tar content that is no longer consistent with the original classification.
Hot-Recycling of Tar-Containing Asphalt Pavements

During the lifetime of a road, trenches are excavated to repair water pipes, new cables installed for television networks, etc. Especially in cities, road pavements look like a patchwork after a short time.

To overcome this problem of inadequate classification, the Swiss Federal Office for the Environment (BAFU) enacted a guideline on the re-use of waste and fixed a limit value of 5000 ppm for the sum of PAH as defined by the U.S. Environmental Protection Agency (EPA-PAH) in the binder of new pavements (BAFU, 2006). However, this limit value was not based on occupational health factors but was a compromise between political, economical and ecological considerations. Various interest groups have regularly challenged this value, suggesting both lower and higher limit values. Motivated by the lack of sound emission data, Empa launched a research project to provide the scientific knowledge to fix a limit value based on exposure values and occupational health considerations.

The research project was divided into two parts: A laboratory study to investigate the effect and importance of various parameters, such as PAH concentration, temperature and viscosity, on the emission of fumes and PAHs (Hugener et al., 2007a). Field tests were then carried out to get information on the emission behaviour in the field and to obtain personal occupation data (Hugener et al., 2009). The present paper is a combined analysis of laboratory and field data, leading to more general conclusions and legal consequences and suggestions with respect to emissions from hot-recycling of tar-containing asphalt pavements.

2. Laboratory testing

2.1. Fume generation

The first challenge was the laboratory production of fumes that are representative for the fumes during paving. The adequate procedure has previously been heavily disputed (CONCAWE, 1992) as a result of published emission data for pure bitumen (Niemeyer et al., 1985; Sivak et al., 1989). For these studies, bitumen was heated to very high temperatures to get enough condensates out of the emitted fumes for skin tests on mice. The higher the temperature, the more fumes are produced, but also the more cracking is taking place, producing toxic decomposition products (Kriech et al., 1999). This may result in fume compositions that are radically different from bitumen fumes during paving.

For this reason it is essential to use a fume generator producing fumes in compositions that match the fumes emitted during paving as closely as possible. However, no standard fume composition can be defined as the fumes are dependent on the type of bitumen used, as well as on temperature, paving procedures and other factors.
A literature search revealed two predominant fume generation methods which have been validated in the field. A simple fume generator was designed and validated by Brandt et al. It consists of an open glass flask containing the bitumen, which is heated in a temperature controlled heating mantle (Brandt et al., 1999; Brandt et al., 1985; Brandt et al., 1994). Fumes are collected by two or more sampling devices mounted on top of the flask. Another fume generator was developed by Kurek et al. to produce fumes for animal inhalation studies to test the carcinogenic potential of bitumen fumes (Bonnet et al., 2000; Brandt et al., 2000). This fume generator consists of a hot inclined surface enclosed in a sealed box. Bitumen flows in a thin film down the plane under rigidly controlled conditions (Kurek et al., 1999). This setup is quite sensitive to various test conditions and large amounts of bitumen are needed. One significant advantage is the constant composition of fumes throughout the whole experiment, which is not the case with the simple fume generator of Brandt due to the depletion of volatile components. Despite this limitation, the fume generator described by Brandt was selected and further improved, because in our case, the fume was not detected continuously but sampled in batches. Furthermore, the scarcity of tar binders, which are no longer produced in Switzerland, would not have permitted the use of the device described by Kurek et al.

2.2. Sampling and chemical analysis

Despite the simple construction of the fume generator, sampling of the emitted fumes proved difficult. The slightest air movement caused an inhomogeneous fume repartition above the vessel. To overcome this problem, a small, dedicated fan was mounted vertically above the fume generator and the fume generator was enclosed with cardboard rising 15 cm above the vessel (Figure 1). Homogeneity was confirmed through repeated measurements from two sets of sampling units set up diagonally over the flask opening.

Fumes of tar-containing binders contain both high- (2- and 3-ring) and low-volatile (4- to 6-ring) PAHs. This required a sampling unit consisting of two parts: a teflon-coated glass filter to collect the particle-bound and condensed PAHs, and a backup adsorption tube (ORBO-43, XAD-2) placed between the filter and the sampling pump for volatile PAHs.

Filter residues were weighed for the gravimetric determination of total particulate matter (TPM). Afterwards, filters and adsorption tubes were extracted with toluene and the combined solution was analysed by GC/MS (Gas chromatography combined with mass spectrometry) and RP-HPLC (Reversed phase high performance liquid chromatography). Concentrations of all 16 EPA-PAHs in the fume were determined both in the laboratory and in the field tests. The sampling and chemical analysis are described in more detail in (Hugener et al., 2007a) and in the original report (Hugener et al., 2007b).
2.3. Validation of the sampling procedure

Several aspects were investigated to validate the laboratory setup and sampling procedure. These included the performance of analytical methods for TPM and PAH analysis, and the homogenous and repeatable fume generation and sampling. The optimisation of the laboratory procedures was critical because the binder is at first solid and must be heated rapidly to the target temperature. Then, the fume composition should remain constant during a relatively long period to allow representative samples to be taken.

Therefore, the temperature ramp, the starting point and the duration of the sampling are key parameters. Sampling time has to be adjusted to collect enough material for the chemical analysis while remaining within the capacity range of the adsorption tube. To a certain degree, this can also be met by adjusting the flow of the sampling pumps. However, sampling speed is also used to account for changing amounts of TPM and PAH emissions which can vary by several magnitudes depending on the experimental parameters.
Figure 2. Temperature and emissions in the validation experiment

To determine the best starting point and sampling time, three consecutive samples of about 1 hour each were taken in a preliminary experiment. Changing the full sampling and filter units was accomplished in about 5 minutes. In addition to the offline TPM and PAH analysis, emissions were also measured continuously with a flame ionization detector (FID).

Figure 3. PAH-emission of the three sampling periods expressed in percentage of the total PAH-emissions
The temperature was first measured in the glass flask while the still solid binder was heated. After approximately 20 minutes, the sample became partly fluid, the temperature probe was stuck into the binder and the sampling pumps were turned on. Mechanical stirring began about five minutes later when the binder was fully liquefied. The FID signal showed a marked increase when the stirrer was first activated and reached its maximum shortly before the final temperature was reached. After this, the FID response decreased slowly throughout the rest of the experiment (Figure 2), indicating that the FID active emissions are not in steady-state. This is well explained by the data, representing subsets of the EPA-PAHs, shown in Figure 3. Constant emissions would be reflected in a linear increase of the cumulated PAH emissions. This is largely observed for 4, 5- and 6-ring PAH, with a slightly smaller slope during the first sampling period, as can expected because the target temperature had not quite been reached. In contrast, Naphthalene, the only 2-ring PAH, showed a completely different behaviour. More than 70% was emitted during the first period, indicating a rapid depletion of Naphthalene in the binder.

We considered three ways to cope with the rapid depletion of Naphthalene: (i) using a larger amount of binder while keeping its surface and thus volatilisation constant, (ii) excluding Naphthalene from the list of analyzed PAH, which implies that EPA-PAH, a widely used sum parameter, cannot be determined, and (iii) reducing the sampling time to minimize Naphthalene depletion.

Because we did not want to completely redesign the experimental vessel nor abandon Naphthalene, we chose a sampling time of 60 minutes and further improved the heating step to reach the target temperature within 10 minutes after starting the sampling. We have previously shown that the PAH composition in the laboratory fume and in the field is similar except for the Naphthalene (Hugener et al., 2009). This is consistent with the above experiment, assuming that considerable amounts of Naphthalene are lost during the initial construction of the pavement with the tar-binder.

2.4. Test program

In a first set of experiments, pure tar hv54 and a pure bitumen were blended to study mixtures with different PAH contents (Table 1). The influence of temperature on the emission behaviour was studied between 140 and 240 °C. This is the range of paving temperatures used in the field for hot mixes and mastic asphalt. However, at temperatures above 210°C, fume generation was so strong, that the described sampling units were overloaded. To study emissions from mastic asphalt in detail, the sampling procedure and the fume generation would have to be adapted.
Table 1. Test parameters of the laboratory experiments

<table>
<thead>
<tr>
<th>Binder composition (% w/w)</th>
<th>EPA-PAH content of the binder (mg/kg)</th>
<th>Test temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar hv54</td>
<td>Tar binder TB 2000</td>
<td>Bitumen 50/70</td>
</tr>
<tr>
<td>0</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>99</td>
</tr>
<tr>
<td>2.5</td>
<td>0</td>
<td>97.5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>50</td>
</tr>
</tbody>
</table>

3. Field testing

Up to now, most experiments dealing with occupational health effects of paving workers used pure bitumen as a binder. Limited data exist concerning the level of exposure and subsequent health effects when tar-containing binders are used. This is because tar binders are no longer used and are known to be dangerous. In Germany, even pure bitumen fumes are a matter of dispute and hence the bitumen producers are busy enough investigating the emissions of pure bitumen (Pohl et al., 2006a; Pohl et al., 2006b; Preiss et al., 2006; Rühl et al., 2007). In Switzerland, the low German and Austrian limits for the recycling of asphalt are not generally accepted, because they are not based on emission studies.

In the US, the National Institute for Occupational Safety and Health (NIOSH) and the Department of Transportation, Federal Highway Administration (FHWA) declared fumes a priority for non-regulatory action. Since 1997, a guideline produced by a cooperative effort between the asphalt industry, NIOSH, and FHWA advises the installation of exhaust ventilation systems at the auger area of the paver, where fumes are generated, for all new self-propelled HMA pavers weighing 16,000 pounds or more to reduce the impact of fumes for the roadmen (NIOSH, 1997).
Main emission sources and total emission

In order to determine the total emission in the paving process the main emission sources have to be considered. These were judged to be located as follows (Figure 4):

– The material hopper, where the hot mix is filled in the paver,
– The auger and screed area of the paver, where the asphalt concrete is mixed, distributed and precompacted,
– The fresh pavement after the first compaction by the paver.

Figure 4. Enclosed paver and main emission sources

In our studies, the three emission sources were measured separately. For this purpose the paver had to be adapted with removable enclosures over the material hopper and auger area, optimized by fume experiments. Two chimneys with a ventilator on the top were installed on the paving machine. Tubes connected the chimneys with the enclosed material hopper and the auger area. The flow through the chimneys was adjusted to 8 m$^3$/min each. Both chimneys were equipped with a set of instruments to measure temperature, air velocity and volume as well as sampling devices to collect PAH-emissions and particulate matter.

Emissions from the pavement surface were sampled with a modified FLEC-cell (Wolkoff et al., 1998) of 150 mm diameter and a constant air flow of about 600 ml/min. The supplied air current was slightly higher than this to prevent the outside air from entering, because it could be contaminated by the exhaust fumes of the working machines.

Occupational health data were obtained from 7-8 paving workers equipped with personal samplers. Sampling was performed by deposition and adsorption on membrane filters in open-face filter holders, followed by PAH-adsorption tubes (Hugener et al., 2007b). Four additional personal samplers were permanently fixed on the paver.
4. Results and discussion

4.1. Laboratory tests

Figure 5. Emissions vs. PAH content in the binder at 160°C

PAH emission was expected to be a function of the PAH content in the binder. At first glance this is virtually true for TPM as well as for Benzo(a)pyrene and the sum of 16 EPA-PAHs (Figure 5). However, a closer look reveals that this is not true for TPM at PAH concentrations in the binder below 5000 ppm, where TPM emissions are nearly independent of the original PAH content.

Temperature is the most important factor on the emissions as can be seen in Figure 6. TPM and Benzo(a)pyrene emissions increase almost exponentially with temperature. The temperature dependence can be approximated by the exponential function exp(1/T). This same function also describes the vapour pressure of individual chemical compounds. Emissions of TPM and Benzo(a)pyrene double with a temperature increase of approximately 12°C. This is consistent with the findings of Brandt who investigated the emission behaviour of different bitumen (Brandt et al., 2000; Brandt et al., 1992). However, the temperature dependence for the sum of the 16 EPA-PAHs is distinctly different, showing an almost linear and only modest increase with temperature. This is most likely the effect of the rapid transfer into the gas phase of the high-volatile PAHs. At higher temperatures, and with increasing time, this leads to a significant depletion of the respective substances in the reaction vessel. Because high-volatile PAHs represent 90% of EPA-PAH in the emission, they dominate the behaviour of the cumulated PAHs.
Figure 6. Temperature influence on the emission behaviour of a binder containing 5100 mg/kg EPA-PAH

Figure 7. Temperature dependence of TPM emission for two binders with different PAH content

Surprisingly, TPM emission is less influenced by the PAH content in the binder than expected. At 160°C, emissions are almost identical for the two binders with a
PAH content of 500 and 5100 mg/kg (Figure 7). This indicates, that, for a total PAH content below 5000 mg/kg, bitumen is the main emission source for TPM at temperatures below 180°C. Looking at higher temperatures, tar contributes significantly to the TPM emissions: at 210°C TPM content is 50% higher for the binder with 5100 mg/kg PAH.

4.2. Field tests

Three field tests were carried out in different parts of Switzerland (Table 2). In the first field test, the hot mix contained almost no tar, which is reflected by the low PAH-content of the extracted binder. The second field test took place in a tunnel, which is a rather uncommon situation. As reported by the paving workers, ventilation was exceptionally good and a wind velocity of 0.7 m/s was measured. EPA-PAH-content of the paving material was slightly above the Swiss limit of 5000 mg/kg. In field test 3, where a bicycle lane was constructed, emissions were expected to be smaller as the lane is about half the width of a regular road lane.

The scatter of the measured values from the personal samplers was larger than the difference between the results with and without coverage of the auger and the material hopper.

Table 2. Field objects

<table>
<thead>
<tr>
<th>Field test 1</th>
<th>Field test 2</th>
<th>Field test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>National highway A2, breakdown lane</td>
<td>Highway tunnel with 2-lanes</td>
</tr>
<tr>
<td>Material</td>
<td>Wearing course, asphalt Concrete 32 mm with 30% RAP</td>
<td>Wearing course with 65% RAP</td>
</tr>
<tr>
<td>Paving temperature</td>
<td>155±5°C</td>
<td>146±4°C</td>
</tr>
<tr>
<td>EPA-PAH-content in the binder</td>
<td>180 ±30 mg/kg</td>
<td>5600 ±300 mg/kg</td>
</tr>
</tbody>
</table>

The capture efficiency corresponds to the fraction of the total emissions, coming from the material hopper and augers, which are evacuated through the ventilation. This capture efficiency was determined in the field using SF₆ as an inert tracer, which was dosed at a known rate, sampled in Tedlar bags and quantified using gas chromatography with an electron capture detector (GC-ECD). The so determined capture rate was 24%, which is in contrast to the 80% recovery rate demanded in the American guidelines. Our enclosure was a temporary and removable retrofit (Figure 8), which can not be expected to be as efficient as the specially designed...
pavers in the USA. Furthermore, the capture efficiency is determined indoors in the NIOSH Engineering guidelines (Brandt et al., 1992; NIOSH, 1997), which will lead to more optimistic values. We, nevertheless, assume that even with excellent engineering it will be difficult to exceed 50% capture efficiency in long term, rough field applications.

Figure 8. Enclosed auger/screed area of the paver

4.2.1. Main emission sources

The distribution of the emissions to the presumed main sources can, nevertheless, be determined by taking into account the corresponding capture efficiency. In field test 3, a different paver was used which was, however, enclosed using the same technique. Some differences in the results might still originate from the different paver model.

Total mass flow was estimated from the measured concentrations at the three main sources and the corresponding air flow, taking into account the measured capture rate. The calculated mass flow amounted to 79 g/h and was clearly below the limit value of 500 g/h for particulates, defined in the Swiss regulation on air pollution (LRV, 1985). In principal, this limit value is valid only for the emission of stationary sources, but it may be used for diffuse or mobile emissions, such as the paving of road, as a guiding value.

The auger area is clearly identified as the main source with 55 to 85 percent of emissions (Table 3). The rest of the emissions come from the material hopper (9-25%) and the pavement (5-2%). In the case of the emitted fumes from the fresh
pavement, there is a significant difference between the TPM and EPA-PAH-value. As the surface temperature of the compacted pavement decreases, only the volatile compounds are emitted. Because the high volatile compounds are passing through the filters and are collected only in the adsorption tubes, the TPM-value, which represents the lower and non-volatile compounds is lower at the colder sources than where the asphalt mix is hotter, which is at the auger and the material hopper.

### Table 3. Main emission sources

<table>
<thead>
<tr>
<th>Site</th>
<th>Parameter</th>
<th>Emission [mass-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Auger</td>
</tr>
<tr>
<td>Field test 2</td>
<td>TPM</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>EPA-PAH</td>
<td>80</td>
</tr>
<tr>
<td>Field test 3</td>
<td>TPM</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>EPA-PAH</td>
<td>55</td>
</tr>
</tbody>
</table>

### 4.2.2. Concentration of particulate matter

Particulate matter consists of the compounds which are retained by the filter. Mass determination is inexpensive and gives a rough estimate of the total amount of emissions and therefore, a limit value for TPM is fixed in many countries. Different countries, however, use slightly different measuring methods. The limit value for bitumen fumes is 10 mg/m³ in Switzerland and Germany, and 5 mg/m³ in the USA (TRGS, 2006; NIOSH, 2005; MAK, 2009).

### Table 4. Results of the field tests

<table>
<thead>
<tr>
<th>Field test</th>
<th>Field test 1</th>
<th>Field test 2</th>
<th>Field test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPM</td>
<td>0.3 - 0.6</td>
<td>0.6 – 3.9</td>
<td>0.3 – 1.7</td>
</tr>
<tr>
<td>fixed on the paver</td>
<td>nd</td>
<td>0.8 – 3.8</td>
<td>0.1 – 2.8</td>
</tr>
<tr>
<td>paving workers</td>
<td>nd</td>
<td>0.7 / 2.0</td>
<td>1.3 / 2.8</td>
</tr>
<tr>
<td>BaP</td>
<td>0.01 - 0.05</td>
<td>0.1 - 0.7</td>
<td>0.00 - 0.04</td>
</tr>
<tr>
<td>fixed on the paver</td>
<td>nd</td>
<td>0.01 - 0.20</td>
<td>0.00 - 0.02</td>
</tr>
<tr>
<td>paving workers</td>
<td>nd</td>
<td>0.06 / 0.11</td>
<td>0.03 / 0.07</td>
</tr>
<tr>
<td>driver</td>
<td>nd</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nd: not determined.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the field tests, the maximum TPM content was 3.8 mg/m³ and hence below the Swiss limit value of 10 mg/m³ (Table 4). TPM concentrations are strongly scattered, which is typical for outdoor emission measurements. In addition, paving workers work at different positions under changing fume concentrations. Concentrations of BaP in field test 3 seem to be lower than in field test 2. This may partly be due to the lower contamination of the RAP and the smaller lane width. However, the data is strongly scattered, and local meteorological conditions were not monitored or modelled. Therefore, a detailed interpretation of this aspect is not feasible at this point.

5. Conclusions

Occupational health data obtained from the field tests in this research study show that emissions from RAP containing tar are all within the range of the Swiss limits of workplace concentrations (MAK, 2009). However, the margin to maximum allowed values is not large, especially for the measured TPM values. Furthermore, all three field tests took place under rather favourable conditions, because ventilation and wind velocities were relatively high. Because of the large scatter of data, they should be verified with additional field tests.

It has been clearly demonstrated that the main emission source is the auger area, where the hot asphalt is mixed and distributed, but it has also become evident that the enclosure and capture of the emitted fumes from the auger area is difficult. In practice it would be highly challenging to obtain a capture efficiency of 50%, and even minimal ventilation is prone to somewhat hinder the paving process. Therefore, the enclosure of the paver is not recommended.

From the viewpoint of occupational health and based on the data of this study, the limit value of 5000 mg/kg EPA-PAH in the binder of the new hot mix, as fixed in the current guideline [2], is acceptable. This is true for paving temperatures below 160°C and sufficient ventilation or wind velocity. Still, the use of other techniques with lower paving temperature, especially cold recycling, should be encouraged for tar-containing RAP. In addition, the re-use of highly contaminated RAP with EPA-PAH binder contents above 20000 mg/kg (approximately equivalent to a tar content of 10%) should be banned because the dilution of highly contaminated material is ecologically not advisable. Before the introduction of parallel drums, asphalt mixing plants could add no more than 25% RAP due to technical reasons. This technical limitation resulted in a dilution by at least a factor of four and thus EPA-PAH contents below 5000 ppm in the final mix, as long as 20000 mg/kg EPA-PAH in the RAP was not exceeded. However, the latest generation of asphalt mixing plants can handle the addition of more than 50% RAP. Consequently, it is necessary to have a limit of 5000 mg/kg EPA-PAH (relative to the binder) in the final mix in addition to the 20000 mg/kg limit in the RAP to maintain the current safety level.
Acknowledgements

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6. Bibliography


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