Sustainability & Environment

Paving the way to an improvement in air quality

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Abstract

Air quality, especially in metropolitan areas, is a topic of intense discussion and focus, with many city authorities setting targets with the aim of improving air quality and reducing issues related to poor air quality. There are a number of sources which contribute to a deterioration in air quality, these include vehicles, thermal power plants, waste management facilities and construction activities, to name a few. Although emissions from road construction and maintenance activities may not contribute as significantly to air quality related emissions from other sources, reducing the impact of these activities should be considered as playing a part in a holistic approach to improving the air quality of cities. This paper describes a bitumen additive which, in field trials and laboratory testing, has been shown to reduce emissions from bitumen and asphalt mixtures during storage, asphalt manufacture and pavement installation. Laboratory experiments designed to replicate the various aspects of the bitumen supply chain; starting from refineries and storage depots to paving at road construction sites are presented. The laboratory results have shown substantial reductions in a range of air quality indicators, such as SOx, NOx, particulate emission, volatile organic content emission as well as in other potential nuisance vapours such as H2S and odour causing compounds. In addition to the laboratory studies, full scale field evaluations carried out in major cities have reflected the results obtained in the laboratory and show a reduction in the emissions at various points of the asphalt preparation and pavement laying process. Bitumen containing this active additive could play a role as part of a solution in helping to improve air quality in cities.

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1 Introduction

'Air quality' refers to the condition of the air within our surroundings [1,2,3]. Good air quality is the degree to which the air is clean, clear and free from pollutants such as smoke, dust and smog among other gaseous impurities.

Air quality is determined by assessing a variety of indicators. An Air Quality Index (AQI) is a number used by many government agencies [1,2,3,4,5] to communicate to the public the current quality of the air or how the air quality might change in the future, a little like a weather forecast. Different jurisdictions [2,3,4,5] have their own air quality indices, corresponding to particular air quality standards, but all tend to follow similar principles. It is known generally that there are a mixture of different compounds of gases i.e. nitrogen oxides, sulphur dioxoide, carbon monoxide, particulate matter (PM), Volatile Organic Compounds (VOCs) etc. which can be released from bitumen and asphalt mixtures at elevated temperatures that may impact air quality in the immediate vicinity of an operating asphalt plant or during paving applications. Generally, the gases from bitumen and its application are normally present at low levels in outdoor air [6,7,8] when compared with other industries. Specific gases and particulates from hot mix asphalt (HMA) plants which impact air quality are categorised under two types of emissions, *ducted sources* and *fugitive sources*. The primary sources of specific gases and particulates associated with asphalt production are the dryers, hot bins, and mixers, which emit PM and a variety of gaseous emissions during production [9,10,11,12,13]. However, very few studies are carried out to understand the emissions evolved related to air quality during bitumen usage and application for road industry [14,15,16,17].

Other sources of specific gases and particulates found at asphalt plants and paving applications are shown in Figure 1.

Key

1: Hot liquid bitumen storage tanks.

2: Asphalt production

- ✓ Asphalt storage silos which temporarily store the asphalt;
- ✓ Truck load-out operations, in which the loose asphalt mixture is loaded into trucks for hauling to the job site;
- ✓ Hot oil heaters, which are used to heat the asphalt storage tanks;
- ✓ Yard emissions, which consist primarily of fugitive emissions
- ✓ Most of the other potential specific gases and particulates, such as the dust generated during the drying of aggregate, are captured by baghouse filters or similar controls and not released to the environment.

3: Asphalt in truck beds and the discharge of loose asphalt mixture from truck to paver tipper

4: Asphalt laying and compaction at paving sites.

Other sources: Vehicular traffic generating CO, NO and fugitive dust on paved and unpaved roads while aggregate material handling, and other aggregate processing and drying operations.

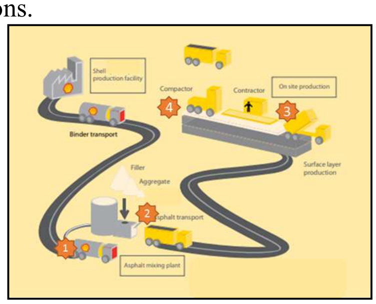

Figure 1: Schematic diagram to indicate the locations to measure gases and particulates

Shell investigated the impact of its innovative bitumen technology Shell "BitufreshAir" which reduces emissions from bitumen and asphalt mixtures during storage, asphalt manufacture and pavement installation.

2 MATERIALS AND CHARACTERISATION

Shell Bitumen FreshAir is a total solution for both conventional (Penetration) and Polymer Modified Bitumen (PMB) grades. It contains of an innovative active additive technology and was developed over a number of years. The mixture of inhibiting components of additive act directly with selective compounds which are the source of gases, particulates and odour releasing molecules in bitumen.

2.1 Laboratory testing

Shell's global R&D team conducted an extensive laboratory study which examined a range of twenty bitumens from different geographical regions spanning a wide range of grades from very hard (10/20dmm penetration grade) to very soft bitumens (160/220dmm) from different refineries and 14 PMB samples i.e. laboratory prepared and plant prepared PMB.

The laboratory experiments were designed to simulate the end-to-end application from bitumen storage, transportation, asphalt mixing (and compaction) and early pavement life to investigate the impact of Shell Bitumen FreshAir for conventional (PEN) and PMB grades in relation to different air quality indicators.

The studies include analysis of specific gases emitted from bitumen, PMB during storage at elevated temperatures (140 -180°C) for two weeks duration.

Specific gases and particulates were measured from asphalt mixing at multiple temperatures – 140, 160 and 180°C, and early life of the pavement at room temperature and at 60°C.

Additionally, any potential impact on its properties, characteristics and asphalt mixture performance was assessed using Shell Bitumen FreshAir for conventional (PEN) and PMB grades.

2.2 Testing and Analysis:

Various testing and analytical methods were used, developed or modified to measure the number of gases and particulates during the study to correspond to various stages of the bitumen, PMB supply chain and its application:

2.2.1 Bitumen testing:

In the laboratory, to study the storage effect, bitumen, PMB was stored in an aluminium toothpaste tube and placed in a vertical static position in the oven at multiple temperatures over a period of time and specific gases (SO_2, CO, NH_3,) as well as in other potential nuisance vapours such as H_2S and were measured in vapour space i.e. 30% headspace (the air left above the content in the closed aluminium toothpaste tube).

Gaseous emissions were measured using different Dräger sampling tubes and systems enabling the identification and measurement of different gases (SO_2, CO, NH_3) and potential nuisance vapours such as H_2S. These tubes are glass vials filled with a chemical reagent that reacts to a specific chemical or family of chemicals. A calibrated 100ml sample of air was drawn through the tube with a Dräger Accuro® pump from the aluminium tooth paste tube. Multiple gaseous tubes with varying detection ranges were used.

Volatile organic content and semi-volatile organic content were measured using an analytical technique that combined separation properties by gas chromatography (GC) with the detection feature of Mass Spectrometry (MS) and Flame Ionization Detector (FID) to identify different substances within a test sample in the headspace i.e. the air left above the contents in a sealed container.

2.2.2 Asphalt preparation and testing:

A 30 litre asphalt mixer was used to study the emissions from hot asphalt mixtures. The measurements were carried out at three temperatures, viz. 140, 160 and 180 °C. These temperatures were selected to cover the normal range of temperatures for asphalt mixtures. For gases like SO_2, NO, NO_2, NH_3, CO, H_2S and the $PM_{2.5}$ and PM_{10} it was not possible to directly measure the emissions since the detectors did not have a sampling pump to withdraw the air sample for analysis. To withdraw samples from the 30L asphalt mixer the detectors were kept in an enclosure through which a continuous stream from the headspace in the mixer was withdrawn using an air pump, at a flow rate of 2.0L/min. Specific gases (NO, NO_2, NH_3, SO_2,),particulate matter ($PM_{2.5}$, PM_{10}) and potential nuisance vapours such as H_2S were measured in a 30 litre mixing unit with special modification to the mixer in order to control the dilution of emissions while mixing in the mixing unit. The measurements were carried out at multiple mixing temperatures (140, 160 and 180°C) over a period of 20 minutes of mixing.
Specific gases (NO, NO_2, NH_3, SO_2,) and particulate matter ($PM_{2.5}$, PM_{10}) and H_2S were monitored at room temperature and elevated temperatures on the prepared slab at 60°C. The asphalt slab was placed in a plastic enclosure containing both gaseous emission and PM detectors. The sample within the plastic enclosure as shown in Figure 2 was then kept for monitoring in an environmental chamber for a duration of one month.

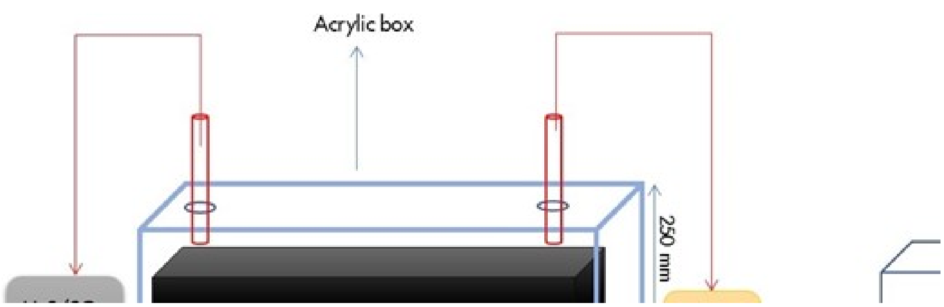

Figure 2: Schematic of experimental setup used to measure the emissions from an installed asphalt pavement immediately after compaction

Table 1: **Devices used for Bitumen and asphalt testing to monitor the specific gases and particulates while mixing and monitoring in environmental chamber**

Specific gases and particulates	Detector used
To measure SO_2, NO, CO, NH_3 in Bitumen and H_2S,	Dräger sampling tubes and system of various range
VOC	Agilent GC/MS-FID
CO, SO_2	Honeywell, BW GasAlertMicro 5
H_2S	Honeywell, BW GasAlertMicro 5
NO_2	Honeywell, BW GasAlert NO_2 EXTREME
NO	Honeywell, BW GasAlert NO EXTREME
NH_3	Honeywell, BW GasAlert NH_3 EXTREME
$PM_{2.5}$ and PM_{10}	TSI Incorporation, USA DustTrak DRX Aerosol Monitor 8534

2.3 Field Trials

To validate the findings of the laboratory study, a number of externally monitored field trials were carried out to assess the efficacy of Shell Bitumen FreshAir as a total bitumen solution for both penetration grade, PMB during real life asphalt production and paving, this was carried to provide a statistical validation of the laboratory results. The results obtained at paving site are reported in this paper.

To minimise field variations as much as possible all field measurements were monitored by an independent environmental agency and consultancy specialising in dust and air quality monitoring. For all field trials same testing plan and methodology was followed with same kind of monitors and devices to detect gaseous and particulate was used.

Trials were carried out using Shell Bitumen FreshAir for penetration in cities around the world – London, (United Kingdom), Saraburi (Thailand) Lelystad (Netherlands), Hongkong, Nantes (France) and PMB - in Guangzhou (China) and Eemnes (Netherlands). The results were analysed to better understand how this solution can help road industry work towards cleaner paving.

2.3.1 Field trials and measuments

The field trial assessments and monitoring guidelines were selected and modified from the US Environmental Protection Agency (US EPA), European Environmental Agency (EEA), and UK Environmental agency to suit the trials that were carried out.

The external agency's equipment (calibrated and certified portable devices) and test methods selected to monitor the indicative emissions were used at all trial sites to minimise experimental set up variations. The same instruments were used for all field trials across the world. The measurements were carried out both upwind and downwind of the various measurement locations across all the activities during paving. All weather conditions were recorded using a portable weather station for all the field measurements. The asphalt mixtures used at the different trials had different mixture designs, aggregates and contained varying quantities (0-40%) of recycled asphalt pavement (RAP) for conventional bitumen and PMB.

At the asphalt plant: measurements were taken at the truck delivery, storage tank, mixing unit and truck loading silos etc, the results are not discussed in this paper. At the paving sites measurements were taken during unloading of the asphalt mixture into the hopper of the paver, at the screed of the paver and behind the paver, during and post compaction. The results provided are an average of these measuments at the paving sites.

3.0 RESULTS

Laboratory testing Results

The studies performed in the laboratory indicate that the amount of gaseous and fume particulates generated during the bitumen usage from end-to-end application varies, depending on the source of the bitumen, the grade of bitumen, the processes used to make the bitumen and the temperature it is used for application.

3.1 Effect of gaseous emission from Shell Bitumen FreshAir –Penetration and PMB

The monitoring of Shell Bitumen FreshAir for both penetration grade and PMB samples resulted in a reduction in the concentration of SO_2 and H_2S measured in the headspace of the toothpaste tubes after 7- and 15-days storage at different temperatures (140-180°C) compared to conventional penetration grades. The studies performed in the laboratory indicate that the amount of gases generated during the bitumen storage varies, depending on the source of the bitumen, the grade of bitumen, temperature and the processes used to make the bitumen.

The data of the 20 bitumens and 14 samples of PMB tested at a different temperature (140 – 180 °C) were given to statistical analysis experts and the conclusions are provided in this paper. The reduction in the SO_2 and H_2S concentrations average a reduction of 25% and were found to be independent of the application temperature (140-180°C), see Tables 2 and 3. Along with nuisance vapour H_2S, which is not part of air quality indicator was measured.

Table 2: Effect of Shell Bitumen FreshAir on the concentration of SO_2 in the headspace of the toothpaste tube – 95% confidence intervals for penetration grades

Time of storage (days)	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
7	25.8	11.1	40.5
15	26.9	15.9	37.9

Table 3: Effect of Shell Bitumen FreshAir on the concentration of H_2S in the headspace of the toothpaste tube – 95% confidence interval for penetration grades

Time of storage (days)	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
7	26.9	14.8	39.0
15	30.3	21.4	39.2

NH_3, CO were detected at very low levels for a few of the bitumens and some were below detection levels (BDL) during the measurements. NO could not be measured due non-availability of Dräger tubes.

Similarly, for PMB, Shell Bitumen FreshAir showed reduction of emissions particularly for SO_2 and H_2S measured as shown in Table 4 and 5.

Table 4: Effect of Shell Bitumen FreshAir on the concentration of SO_2 in the headspace of the toothpaste tube – 95% confidence intervals for PMB

Time of storage (days)	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
7	41.1	19.4	62.8
15	27.4	13.9	41.0

Table 5: Effect of Shell Bitumen FreshAir on the concentration of H_2S in the headspace of the toothpaste tube – 95% confidence interval for PMB

Time of storage (days)	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
7	37.8	26.8	48.9
15	28.4	16.6	40.3

3.2 Impact of Shell Bitumen FreshAir on emissions from hot asphalt mixtures during laboratory mixing

It was observed that NH_3, NO_2, CO and O_3 were not detected in significant concentrations in the 30L mixer over a time of 20 minutes and at all temperatures tested. Air quality indicators, SO_2 and NO were detected in the 30L mixer while mixing the asphalt mixture. Apart from this H_2S was also detected, and whilst this is important to note this is not an air quality indicator. Significant reductions were seen with respect to the concentrations of SO_2, NO and H_2S, irrespective of temperature. Without a rigourous statistical analysis of the results it could be said that the use of Shell Bitumen FreshAir resulted in a decrease in emissions during mixing compared with conventional penetration bitumens and PMB, which could improve indicators of air quality.

The analysis of the data with respect to SO_2 showed a minimum mean reduction of 62 % and NO of 28 %, see Table 6. The temperature of the asphalt mixture was seen to have no statistical influence on the reduction in SO_2 and NO observed.

In case of emissions from the 14 PMBs as shown in Table 7 the analysis of the data with respect to NO showed a mean reduction of 32 %, with lower reduction around 16%. The reductions for SO_2 are comparable with bitumen samples as shown in Table 7.

Using Shell Bitumen FreshAir- for penetration and PMB grades, there is drastic reduction of H_2S on average or greater than 45%.

Data collected on the $PM_{2.5}$ and PM_{10} was not used as stable data could not be obtained, potentially as a consequence of the experimental design. It is recommended that field data be used to evaluate the effectiveness of using Shell Bitumen FreshAir on the reduction in $PM_{2.5}$ and PM_{10} levels for both penetration and PMB.

Table 6: Reduction of SO_2, NO and H_2S observed from asphalt mixtures – 95% confidence interval for Shell Bitumen FreshAir – penetration grades

Gaseous	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
SO_2	90.0	62.2	117.8
NO	57.4	28.5	86.3
H_2S	48.3	9.4	87.2

Table 7: Reduction of SO_2, NO and H_2S observed from asphalt mixtures – 95% confidence interval in Shell Bitumen FreshAir-PMB

Gaseous	Mean reduction measured (%)	Lower bound of reduction measured (%)	Upper bound of reduction measured (%)
SO_2	41.08	19.3	62.8
NO	32.8	16.6	48.9
H_2S	74.6	59.3	89.9

3.3 Impact of Shell Bitumen FreshAir on emissions from hot asphalt pavements and during early life

Measurements of the emissions from the hot asphalt slabs showed that the emissions, if any, were below the detection limit of the detectors used. The detectors used typically had a lower detection limit of 1 ppm. This would indicate that emissions, if any, were extremely small. Emissions from slabs when maintained at 25 °C, 60 °C and 80 °C showed a similar trend, i.e. that emissions, if any, were too low to result in their detection during the course of the experiments.

After 10 bitumens were tested at all three temperatures with no detection of emissions further testing was discontinued.

3.4 Field Measuments

The reduction of specific gases and particulates are presented in Table 8 which are given on an average basis over time, although minimum and maximum reductions were also recorded during the field measurements. The measuments were taken at multiple points at each paving site (unloading of asphalt mixture into paver hopper, at the screed, behind paver and before and post compaction. The results presented in Table 8 are an average reduction of all measurement points of Shell Bitumen FreshAir compared to conventional penetration grades and PMB.

In the asphalt plant, during production i.e. monitors and devices were installed near the mixing unit and during loading of loose asphalt mixture into trucks. Shell Bitumen FreshAir for penetration grades and PMB has shown, on average reduction of gases by 40% along with potential nuisance vapours such as H_2S and odour causing compounds associated with bitumen, modified binder and asphalt mixtures.

In the field gaseous emissions (SO_2, NO, NO_2, VOC, CO) and PM (PM_{10}, $PM_{2.5}$) were reduced on average by 40 % using Shell Bitumen FreshAir compared to conventional penetration and PMB grades during paving application. It was observed that the emissions reduce very quickly and disperse in the atmosphere within the first hour of paving application.

During the field measuments there are many external factors which can impact the outcome of the results like Nantes, France, where PM reduction was impacted by variation in temperatures of mixtures. For Hongkong, the PM_{10} was not captured due instrument failure during measurements.

The field measurements for Shell Bitumen FreshAir for PMB were carried out in Guangzhou province of China on an expressway. The outcome was on average reduction of 60% of specific gaseous and on average reduction of PM by 40%. Figure 3 shows the images of field trial measuments for Shell Bitumen FreshAir.

Figure 3: Field trial pictures for Shell Bitumen FreshAir in Thailand and Netherlands

The effect of temperature on Shell Bitumen FreshAir was also looked at in the laboratory and field. The impact is the same when compared with the outcomes of Shell Bitumen FreshAir for penetration grades and PMB.

Table 8: Overall reduction of specific gaseous and particulate emissions from all the field measurements using Shell Bitumen FreshAir at paving area

Shell Bitumen FreshAir- Penetration grades								
Emissions related to Air quality								**Nuisance**
Location	**SO_2** (%)	**NO** (%)	**NO_2** (%)	**CO** (%)	**VOC** (%)	**$PM_{2.5}$** (%)	**PM_{10}** (%)	**H_2S** (%)
Nantes, France	-50	-54	-41	-81	-33	-28	-28	-40
London, UK	-99	70	-67	-90	33	-88	-90	-90

Saraburi, Thailand	-19	-84	BDL*	-67	-41	-47	-56	-63
Lelystad, Netherland	-50	-25	BDL*	-50	-58	anomalous data		-83
Hongkong	-27	-51	-42	-47	-49	-70	NA	-27
Shell Bitumen FreshAir- PMB								
Guangdong, China	-88	-76	BDL*	-82	-49	-42	-52	-67
Eemnes, Netherlands	-85	-75	BDL*	-54	-38	-63	-38	Cis 100%

*BDL: Below detection level and Cis 100%: gases did not detect with use of Shell Bitumen FreshAir

4 CONCLUSIONS

The outcome of the laboratory findings corresponded well with field measurements in terms of measuring a reduction in specific gases and particulates when mixing and paving asphalt. The paper describes only paving outcomes and not production of asphalt, although there was also a reduction of gases measured.

Each individual trial gave different reduction levels of emissions, overall there is a significant, 40% average, reduction between the concentrations of emissions in terms of SO_2, NO, NO_2, CO, PM, total volatile organic compounds measured from loose mixture (e.g., in a truck, when discharged into the paver hopper) and the road surface, immediately during and after compaction, when using Shell Bitumen FreshAir, under any conditions.

It was observed the emissions reduce very quickly and disperse in the atmosphere within first hour of paving application.

With the field measuments, it is clear that considerable care needs to be taken to account for external parameters which have the propensity to alter the outcome of the field results e.g. type and kind of fuel used, paving equipment, handling of paving instruments, traffic, vehicle movement, location and surroundings of the paving application, weather, particularly wind, along with mixture designs, asphalt type and temperatures.

From laboratory data and field measuments, use of Shell Bitumen FreshAir showed significant reduction of specific gases (NOx, SOx, CO, VOC) and particulates (PM_{10}, $PM_{2.5}$) as well as in other potential nuisance vapours such as H_2S and odour causing compounds associated with bitumen storage, transport, asphalt mixing and compaction. Shell Bitumen FreshAir- penetration grades and PMB shown the reduction levels effectiveness at different temperatures it was used. It can be mentioned that Shell Bitumen FreshAir is a total bitumen solution valid for both conventional (PEN) and premium (PMB) grades. Both continue to deliver an average 40% reduction in specific gases and particulates without changing the specifications.

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