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Effectiveness of the application of water and CMA to abate re-suspension of dust emissions in construction sites - Southwark, London

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1. Summary

This study aimed to assess the efficacy of three different dust-abatement strategies on the resuspension of particulate matter due to the passage of heavy-duty vehicles within the Heygate Estate construction site. The dust suppressants strategies tested during different weeks were: water (applied once per day) and Calcium Magnesium Acetate (CMA) which was applied either once per day or twice per day. All applications were made with a modified grit spreader.

Dust concentrations were continuously measured by an Osiris dust monitor at two monitoring sites located by the sides of a haulage road separated by 10 meters. Dust concentrations due to vehicle passage were calculated for specific wind conditions when upwind-downwind pairs could be defined. The study period lasted 11 months, from April 2014 to March 2015, and three differentiated phases were defined based on the conditions of the road: phase-1 (April-July 2014) and phase-2 (July-December 2014) the surface of the road was tarmac but phase-1 was characterized by demolition activities in the vicinities of the monitoring sites; in phase-3 (Jan-Mar 2015) the surface of the road was unmade.

It was clear from the ambient measurements that construction activities were a source of dust and the monitoring sites located in the haulage road registered a larger number of daily exceedences (daily means > 50 µg m-3) compared to the urban background locations. The monitors recorded between 12 to 16 daily exceedences while the urban background site did not register any for the same period of time. The exceedences days took place only during working days (Monday to Friday).

The application of dust binders to the haulage road effectively reduced the dust levels by 0.72 µg m-3 (water), 0.95 µg m-3 (CMA once) and 1.32 µg m-3 (CMA twice) over the median increment in dust concentration on control days. The largest reductions of dust were attained when CMA was applied twice per day, however, the three methods were not statistically different. Examining the concentrations, the application of CMA either once or twice per day effectively removed the resuspension of dust from the road.

During dry ambient conditions, the three methods registered statistically significant reductions of dust from the road. During wet ambient conditions (defined as RH >70%) only CMA effectively reduced the levels of dust from the road. This suggests that it is not worth applying water in ambient conditions where RH >70% but it is worth applying CMA.

This study clearly adds significantly to the evidence base relating the use of water and dust binders for supressing resuspension and provides useful information for formulating best practice guidance. Any future studies should seek to target roads with a higher throughput of vehicles and make a more accurate assessment of the vehicle passing the measurement site by using an automatic traffic counting system.

2. Introduction

This study aimed to assess the efficacy of three different dust-abatement strategies on the resuspension of particulate matter due to the passage of heavy-duty traffic in a construction site. This has been undertaken within the Heygate Estate construction site (Figure 1) in central London between April 2014 and March 2015. A single haulage road was used but was resurfaced to provide an assessment of efficacy on both made and unmade conditions. The three abatement methods used were:

i. Water

ii. Application of Calcium Magnesium Acetate (CMA), sprayed once a day

iii. Application of Calcium Magnesium Acetate (CMA), sprayed twice a day

Figure 1: Left shows the location of the Heygate estate in London, right shows the made (top) and unmade (bottom) road surfaces

In order to evaluate the efficacy of each method on reducing the re-suspension of particulate matter, a pair of monitoring sites at each side of the haulage road was installed. Upwind and downwind conditions were defined depending on the wind conditions and increments of PM calculated.

2.1. Construction activities as a source of Particulate Matter

Airborne Particulate Matter (PM) is a mixture of solid, liquid or solid and liquid particles suspended in the air. These suspended particles vary in size, composition and origin. Sources of airborne PM in urban areas include both natural (soil, sea salt, etc.) and anthropogenic sources (tail-pipe emissions, tyre and brake-ware, resuspension of particles from the road, industrial emissions, etc.). It has been evidenced that short and long-term exposure to PM is directly linked to cardiovascular and respiratory problems. The European Commission (EC) set an Annual Mean Limit Value (<40 µg m^{-3}) and a Daily Limit Value (< 50 µg m^{-3} less than 35 days a year) to protect population and the environment. Most of the European cities exceed the EU Limit Values and great effort has been put recently to understand the sources, the chemistry and toxicology of PM.

Despite the annual mean PM_{10} objective being achieved across the whole of London in 2014, there are some sites where the daily mean PM_{10} objective was exceeded (www.londonair.org.uk). The largest PM_{10} concentrations are often recorded close to industrial or construction sites (Bergdahl et al., 2004; Barratt and Fuller, 2014; Font et al., 2015). Construction activities are a well-known source of PM to the atmosphere and can have a substantial temporary impact on air quality in the surrounding areas, affecting personal exposure of workers and also population living nearby. Construction activities were estimated to be responsible for the daily exceedences in 25% of the monitoring stations across London in 1999-2001 (Fuller and Green, 2004). According to the London Atmospheric Emissions Inventory (LAEI) construction and demolition activities are estimated to account for 1.3% of the total PM_{10} emitted in London in 2010, while Non-Road Mobile Machinery accounted for a further 10% (LAEI, 2013). Emissions of PM during the construction are associated with demolition and land clearing, ground excavation, cut and fill operations and the construction of a particular facility itself; they might also occur due to the vehicle transport associated with the activity. Dust emissions from construction often vary substantially from day to day depending on the level of activity, the specific operations and the prevailing meteorological conditions (Chang et al., 1999).

2.2. Dust suppressants

Construction sites are generally regarded as fugitive sources of PM and monitoring is needed for regulatory emission control requirements. The Greater London Authority (GLA) and the London Councils launched the 'Best Practice Guidance' in 2006 (GLA-LC, 2006) and a Supplementary Planning Guidance (SPG) in 2014 (GLA, 2014) in order to control PM emissions from construction and demolition activities. Dust control measures and mitigation measures required to ensure the air quality impacts of construction and demolition are minimised effectively.

The application of water is a common mitigation measure to reduce PM emissions from construction activity (e.g. demolition activity, wash wheels of any vehicle leaving construction site, etc.) due to the hygroscopic nature of particles (Kassomenos et al., 2012). Increasing the humidity of particles, especially those with the largest diameter (coarse particles) reduce the re-suspension of particles.

Calcium Magnesium Acetate (CMA) is a dust suppressant made of a combination of dolomitic lime and acetic acid. Spraying a CMA solution onto a surface binds the airborne particles that come into contact with it and prevent resuspension due to the action of wind, tyres or vehicle turbulence. It has proved most effective when sprayed onto unpaved roads where resuspension rates are relatively high (Barratt et al., 2012). CMA has been applied on paved roads in different locations in Europe to reduce resuspension of PM in trafficked roads. Its efficiency has been proved in Sweden (Norman et al., 2006) and Austria (www.life-cma.at) with daily PM_{10} decreased up to 35%. However, other studies based in Germany (Reuter et al., 2010), United Kingdom (Barratt et al., 2012) and Spain (Amato et al., 2014) could not detect a significant PM_{10} decrease in typical urban roads.

For construction sites it was therefore currently recommended that CMA should be considered on haulage routes on and off site during the demolition and construction phases of large development to reduce high levels of airborne PM. However studies assessing its effectiveness are still lacking.

3. Methods

3.1. Study area

The study area is the former Heygate Estate in Central London comprising an area of 90,000 m^2 in Southwark, central London. The old estate buildings were demolished in two phases, starting in April 2011 and completed in November 2014. New domestic buildings, a park, retail spaces and community areas are currently being built as the new Elephant Park.. As such, the principal sources of local emissions of PM were the demolition and construction activities in the surroundings.

Two Air Quality Monitoring Sites (AQMS) were located on opposite sides of Deacon Way (Figure 1b) separated by 10 m; both inlets were at a height of 2.5 m. The traffic along Deacon Way was only associated with the construction activity (construction machinery, delivery trucks, etc.). Public traffic did flow along Heygate Street, which runs parallel south to Deacon Way.

3.2. Measurements

Measurements of PM were made using light scatter monitors from Turnkey (Osiris, Model 2315). These provided continuous mass concentration measurements of Total Suspended Particles (TSP) and PM in different size ranges: <10 µm, <2.5 µm and <1 µm at a 15 minute time resolution. Air was drawn through the instrument at 600 millilitres per minute via an inlet heated to 35˚C to minimise the impact of water both in the condensed phase and that adsorbed by particles. The instrument sizes individual particles using the laser light scattered which is proportional to the size of the particle; this is then converted to a mass concentration using an assumed particle density.

These instruments are widely used, especially around construction sites, and have passed MCERTS certification as an indicative ambient particulate monitor for PM_{10} in the 0-100 µgm-3 range. In this study we have used PM_{10} measurements from the Osiris; to avoid confusion with reference equivalent methods for measuring PM_{10} Osiris measurements are referred to here as 'DUST'.

3.2.1. Quality Assurance

Both instruments were attended every two weeks to adjust the air flow change the particle filter. Nevertheless, their long term comparability due to flow control and sensor drift resulted in some differences in the data which were not representative of ambient concentrations and would have severely compromised the data analysis. Measurements were therefore corrected for drift by referencing ne instrument to the other based on concentrations measured on a Sunday. Given the nature of sources affecting AQMS in Deacon Way, dust concentrations measured by both AQMS-N and AQMS-S were assumed to be identical on Sundays. Hourly concentrations measured on Sundays for each instrument were compared and an offset and scaling factor was calculated by means of Reduced-Major-Axis (RMA) regression (Ayres, 2001; Warton et al., 2006) and applied to AQMS-N. Once the data were corrected for the drift the uncertainty of differences in dust concentrations measured by the two instruments was estimated to be ~3% (Figure 2). Appendix A provides more details about this procedure.

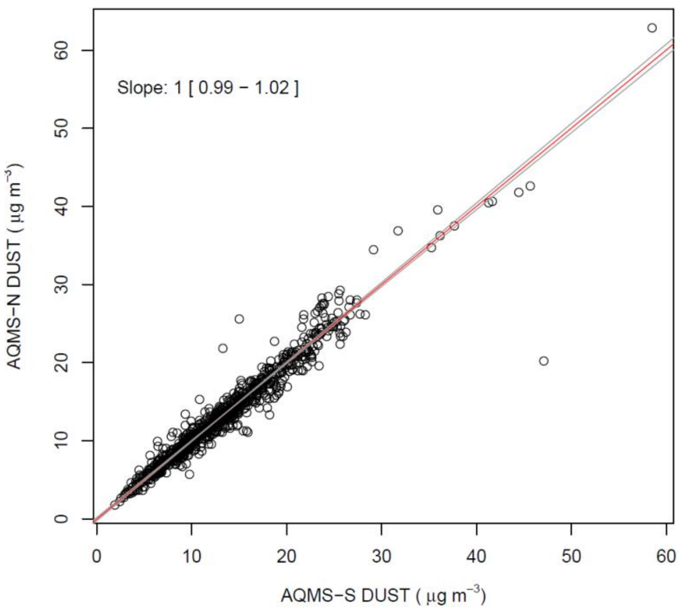


Figure 2. Hourly comparison of the dust concentrations measured in AQMS-N vs AQMS-S on Sundays once the data has been corrected for drift.

3.2.2. Supporting Measurements

Wind direction and wind speed data were taken from a set of meteorological stations across London belonging to the London Air Quality Network (LAQN; http://www.londonair.org.uk/). Although this data does not represent the very local meteorological conditions at the construction site, it offers a good quality data set representative of the synoptic weather conditions in London.

Traffic data was also available from the construction site operators. The times when vehicles entered in the construction site were recorded manually by operators. An average of 25 vehicles per day entered the site.

3.3. Study period

The study period comprises 11 months of monitoring, from 24th April 2014 to 9th March 2015. Three phases were defined depending on the characteristics of the road:

1) Phase-1: from 24th April to 6th July 2014 (75 days). The surface of the road was tarmac and a large amount of demolition activity was occurring south of AQMS-S.

2) Phase-2: from 7th July to 12th December 2014 (159 days). The surface of the road was tarmac.

3) Phase-3: from 13th December 2014 to; 9th March 2015 (88 days, excluding Christmas break). The road was unmade.

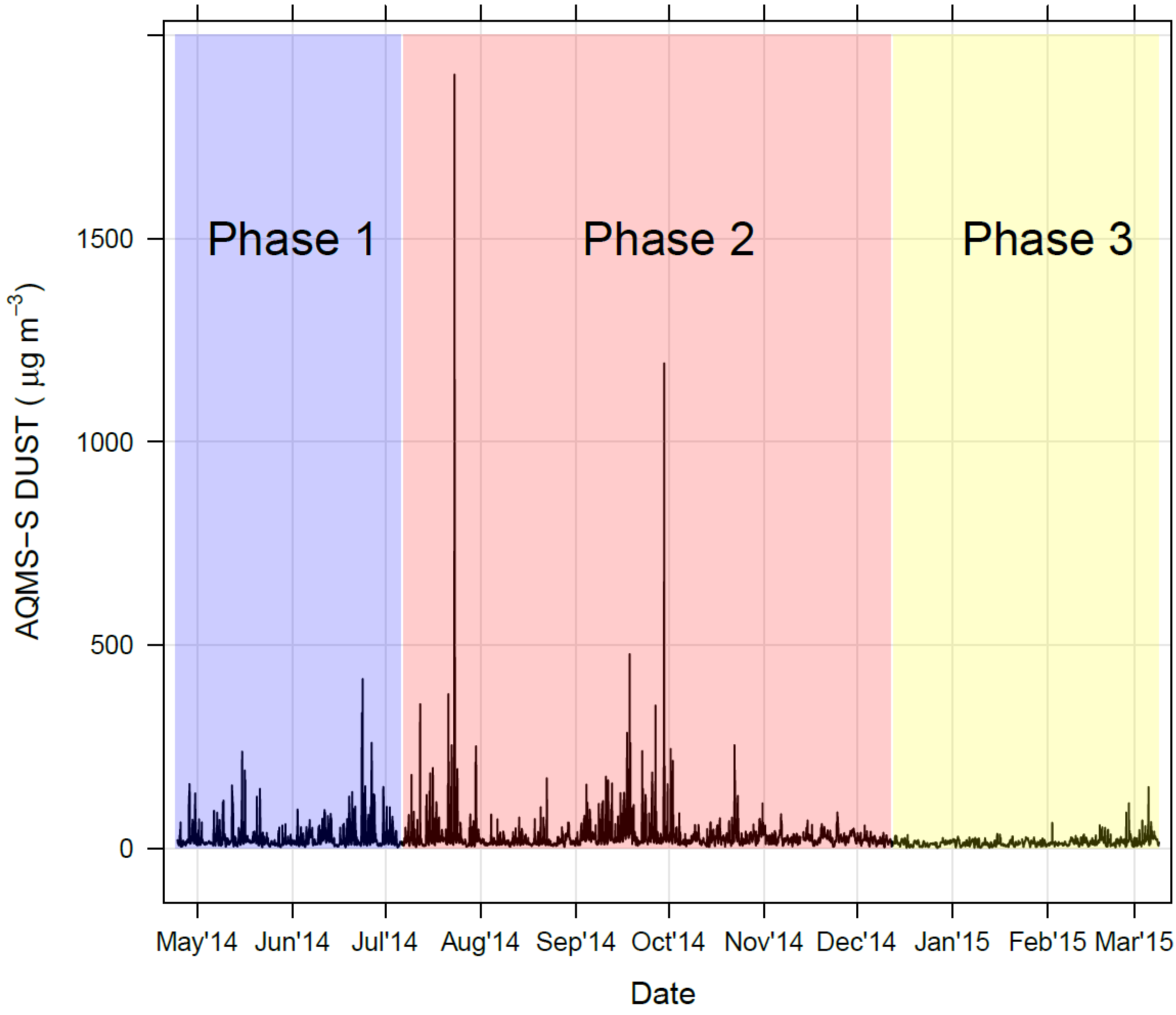


Figure 3. Time series of the dust measured in AQMS-S. Each of the phases is marked in the graph as well.

Public Holidays were excluded from the input dataset and times were expressed in local hours.

3.4. Application of dust binders

The dust binders were applied using a modified grit spreader with the CMA solution being spread at a dose of 20 grams per m^2 across a constant width of 3 m. Spreading is fully automated, with the dosage being adjusted for driving speed, and the dispensing quantity cannot be changed manually by the driver to prevent application errors.

The days and times when dust binders were applied are recorded are recorded in Appendix B. The suppressants were applied early in the morning (single application); and early in the morning and at noon for double CMA application. The dust binders were sprayed by approximately 15-20 minutes.

In the results section the days without application are tagged as “control” or “none” days; “water”, “CMA” indicate the days when those abatement measures were applied; “2xCMA” mark the days when CMA was sprayed twice daily.

3.5. Definition of increments

The increment on mass concentrations of dust due to resuspension emissions from traffic passing by the haulage road is calculated as:

$incDUST = (C\ dust)_{downwind} - (C\ dust)_{upwind}$ Eq. (1)

where *incDUST* was the increment in dust from the road; and *C dust* is the concentration measured downwind or upwind.

The definition of the upwind-downwind conditions was done by means of bivariate polar plots calculated by the Openair software (Carslaw and Ropkins, 2012). These relate pollution concentrations with wind speed (radial axis) and direction (polar axis). Differences in concentration measured at AQMS-S minus those measured at AQMS-N were calculated at hourly resolution for working hours Monday to Friday and bivariate polar plots produced. A minimum of two occurrences were set to calculate the mean difference for a given wind speed and wind direction.

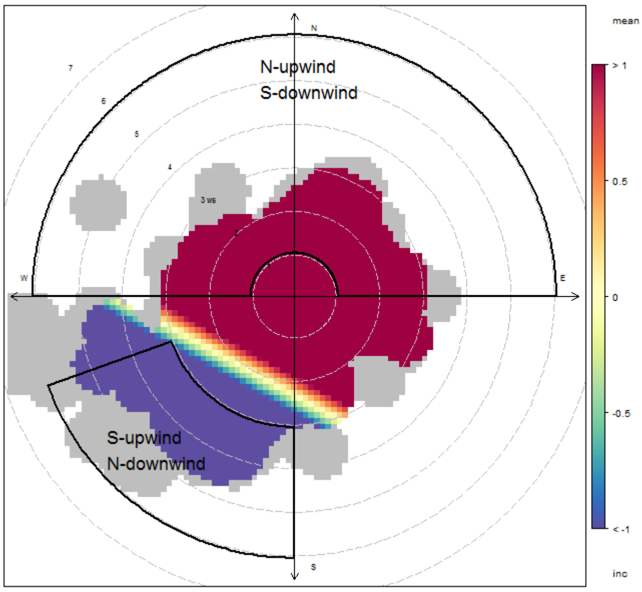


Figure 4: Definition of the wind conditions where each AQMS acted as upwind or downwind conditions in the Heygate construction site based on hourly differences in dust levels measured at AQMS-S minus AQMS-N for working hours on control days. Grey areas indicate that enough data is not available.

3.6. Statistical test

The Kruskal-Wallis one-way test was applied to test if samples of incDUST for the control days and for days when abatement methods were applied originate from the same population. It is a non-parametric method than can be applied to samples that are independent, which may have different sample sizes and variables are non-Gaussian distributed. The null hypothesis (H_0) assumes that samples are from identical populations. H_0 was accepted whenever p>0.05. Otherwise, the alternative hypothesis (samples come from different populations) was accepted.

4. Results

4.1. Temporal dynamics and statistical summary of ambient dust concentrations

The dust concentrations measured at both AQMS in the Heygate construction site exhibited a clear daily and weekly cycle related to the construction activity (Figure 5). Mean concentrations rose very rapidly from 10-20 µg m^{-3} to 40-50 µg m^{-3} at 7 am from Monday to Saturday; and fell at 5 pm (Monday-Friday) and at 12 pm on Saturdays. The dust concentrations on Sundays were lower (~15 µg m^{-3}) and constant during the day. This is in accordance with construction activities being a source of coarse particles. Therefore, working hours were defined based on Figure 7: from 7 am to 5 pm Monday to Friday; and from 7 am to 12 m on Saturdays.

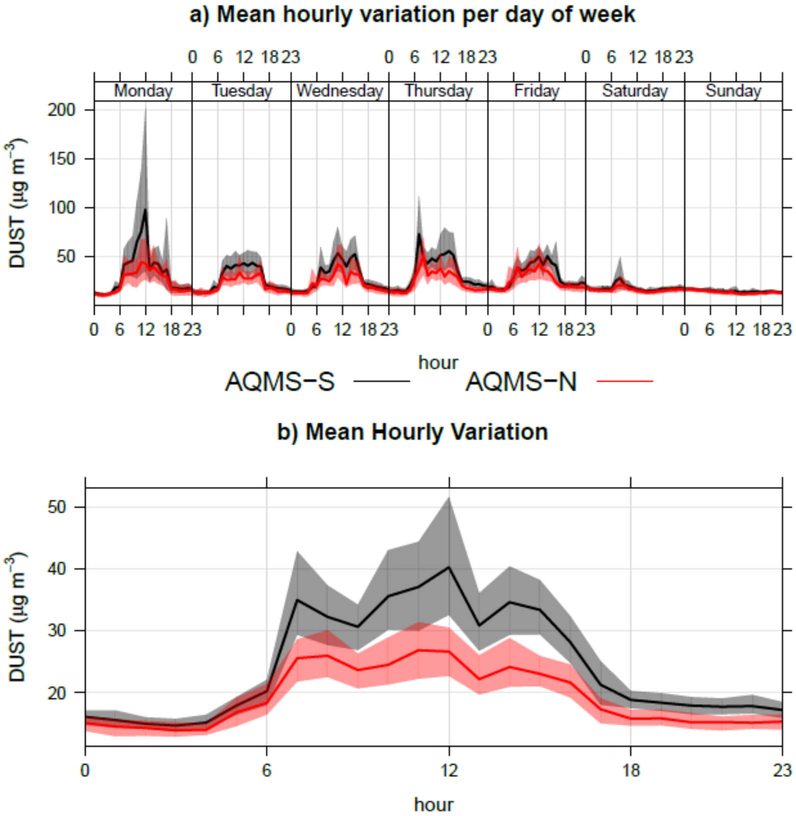


Figure 5: Time variation of the dust concentrations measured at both AQMS in the Heygate construction site for the control days.

Dust concentrations were on average higher in AQMS-S compared to AQMS-N during phase-1 and phase-2 (5 and 16.5 µg m^{-3} higher, respectively). The two monitoring sites measured very similar concentrations during Phase-3 (~15 µg m^{-3}). Phase-2 registered a major number of vehicles passing by the two monitoring sites (an average of 28 vehicles per day) than phase -1 (19 vehicles per day). No traffic data were available for phase-3 after December 2014, giving an average of daily vehicles using the haulage road of one vehicle day^{-1} (Figure 6).

Table 1. Mean ±standard deviation and 25th, 75th percentiles for the dust concentrations measured at AQMS-N and AQMS-S during working hours for the control days per each phase.

	AQMS-N dust (µg m^{-3})		AQMS-S dust (µg m^{-3})		Traffic (# vehicle day^{-1})
	mean ± standard deviation	Median (25^{th}, 75^{th} percentiles)	mean ± standard deviation	Median (25^{th}, 75^{th} percentiles)	mean ± standard deviation
Phase 1	42.1 ± 32.9	33.6 (19.7, 50.1)	47.1 ± 41.5	36.4 (22.3, 57.2)	19 ± 8
Phase 2	28.5 ± 18.8	23.5 (17.9, 33.6)	45.0 ± 59.6	31.9 (21.1, 48.4)	28 ± 2
Phase 3	14.4 ± 7.2	13.4 (9.4, 18.4)	15.0 ± 7.9	13.6 (9.3, 18.8)	1 ± 4

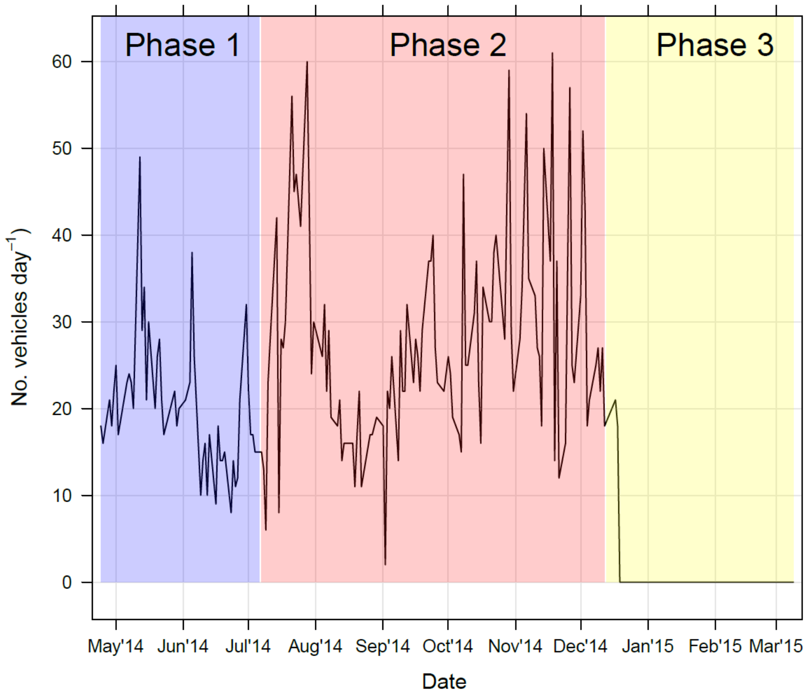


Figure 6. Number of vehicles per day for the working days. The phases of the study are also highlighted.

The phase-1 study period was strongly influenced by demolition activity to the south of the monitoring sites which resulted in higher concentrations as large dust plumes drifted northwards. Mean and 75^{th} percentile concentrations were higher during phase-1 than phase-2.

The days when the dust daily mean concentration exceeded the 50 µg m^{-3} threshold was always on working days. AQMS-N recorded a larger number of daily exceedences (six) than AQMS-S (which registered only 3) during phase-1. That is expected since AQMS-N was downwind more of the time than AQMS-S due to prevailing wind conditions. All exceedance days occurred in control days. However, AQMS-S recorded a larger number of exceedences in phase-2 (13) compared to AQMS-N (only 6). That is because the monitor in AQMS-N experienced a flow fault and did not measure during the days when AQMS-S recorded an exceedance. One of the exceedance days recorded by AQMS-S occurred when water was applied. Any of the AQMS exceeded the daily limit value in phase-3 (Table 2). For the same period of time, the North Kensington urban background site recorded no exceedences.

Table 2: Number of days when daily concentrations higher than 50 µg m^{-3} were recorded at both AQMS-N and AQMS-S.

	AQMS-S	Control	Water	CMA	2xCMA
AQMS-N	Phase 1	6	0	0	0
	Phase 2	6	0	0	0
	Phase 3	0	0	0	0
AQMS-S	Phase 1	3	0	0	0
	Phase 2	13	1	0	0
	Phase 3	0	0	0	0

4.2. 3.2 Definition of increments of dust and temporal dynamics

The bivariate polar plots of the difference in concentration measured at AQMS-S minus AQMS-N are shown in Figure 7 (only data collected during working hours on control days was considered). AQMS-S was representative of the upwind conditions when the wind blew from the southern quadrant SW (180-250 degrees) at wind speeds higher than 3 m s^{-1} (blue areas in Figure 7). Red areas in Figure 7 indicate the wind sectors where AQMS-N measured higher concentrations than AQMS-S (this latter was then downwind). When the wind blew from the north sector, AQMS-N was taken as upwind conditions and AQMS-S as downwind.

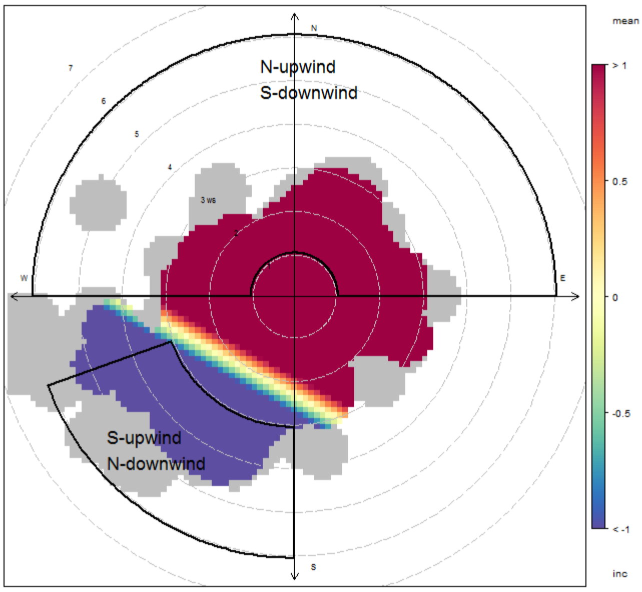


Figure 7: Definition of the wind conditions where each AQMS acted as upwind or downwind conditions in the Heygate construction site based on hourly differences in dust levels measured at AQMS-S minus AQMS-N for working hours on control days. Grey areas indicate that enough data is not available.

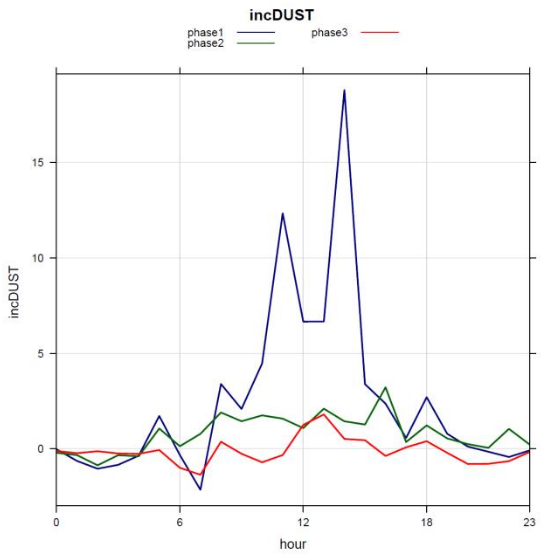


Figure 8: Median hourly daily variation of increments of dust for control days per each phase.

Road increments for dust were calculated for those periods when upwind-downwind conditions were met. The median hourly daily variation agrees with the timing with the construction activity (Figure 8) and therefore associated with the passage of vehicles. Levels of incDUST increased at 7 am to fail again at 5 pm. The maximum hourly incDUST concentration was ~20 µg m^{-3} (phase-1), and less than 5 µg m^{-3} for both phase-2 and phase-3 above the minimum incDUST levels. Little diurnal variability was observed in both phase-2 and phase-3. About 30% of the time the definition of upwind-downwind conditions led to negative incDUST concentrations (36% and 31% of the hourly increments in phase-1 and phase-2, respectively). In phase-3 a large number of negative increments were calculated, about 48% of the hours.

The hourly concentrations of incDUST are therefore strongly associated with the passing traffic.

Figure 9 shows the hourly concentrations of incDUST, number of vehicles per hour and relative humidity for a control period (24-25 June 2014). During non-working hours no vehicles passed between the two monitoring sites and the concentrations of incDUST remained nearly zero. After 7 am vehicles started passing and concentrations of incDUST increased, with peaks up to 25-50 µg m^{-3}.

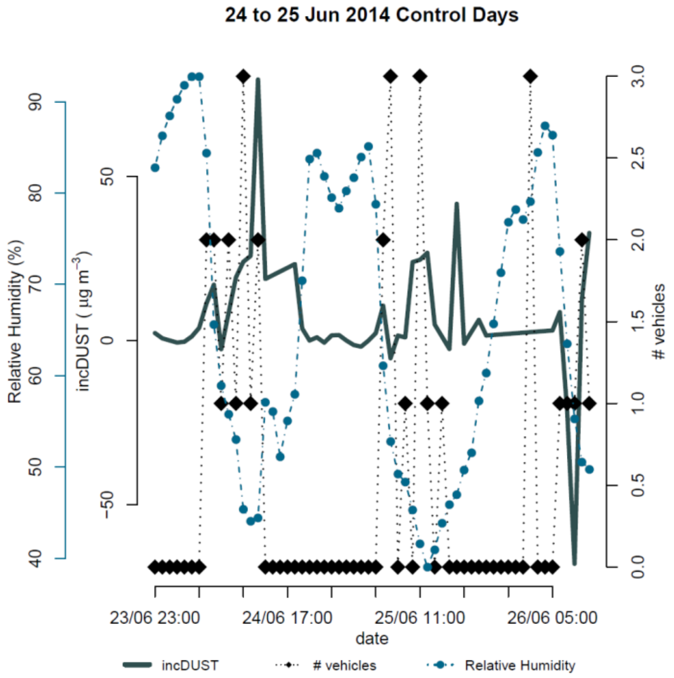


Figure 9: Time series of hourly concentrations of incDUST (grey solid line), number of vehicles (dotted-diamond black line) and relative humidity (dashed blue line) for the 24th and 25th June 2014 (control day).

Figure 10 shows the same type of graph for a period when CMA was applied. It is interesting to note that the peaks of incDUST (up to 20-30 µg m^{-3}) occurred by 7 am when CMA was applied coincidental with the start of the activity (vehicles passing). As for the control days, incDUST peaks were associated with traffic; however, the levels of dust from the road decreased after the application of CMA compared` to the hour before (concentrations of incDUST decreased to ~5 µg m^{-3}).

These two figures show the complex relationship between concentrations of dust from the road, ambient relative humidity and traffic data.

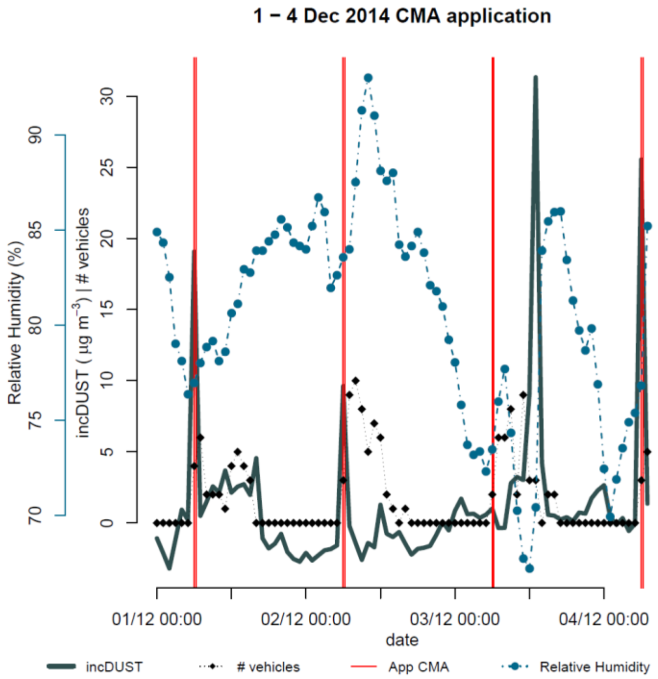


Figure 10: Time series of hourly concentrations of incDUST (grey solid line), number of vehicles (dotted-diamond black line) and relative humidity (dashed blue line) between the 1st and 4th December 2014 when CMA was applied.

4.3. Effect of dust suppressants on ambient air incDUST mass concentrations

In order to evaluate the effectiveness of reducing the dust concentrations from the road, the hourly concentrations of incDUST have been grouped by phases and by abatement methods (water, CMA and 2xCMA). Figure 11 represents the distribution (in a form of a boxplot) of the hourly concentrations of incDUST for control, water, CMA and 2xCMA days. The top lines mark the *p*-value from the Kruskal-Wallis test. Numerical results are summarized in .

For all the results the percentage increment differences can appear large, however, the increment concentration differences are very small (only 1-2 µg m^{-3} between the control and the dust suppressant results); especially when considering mean concentrations of around 30 µg m^{-3}. These results are likely to be within the uncertainty of the instruments and should therefore be interpreted with caution.

Overall, the three methods to abate re-suspension of PM were effective on reducing dust concentrations from the road, with statistically significant reductions of 0.72 µg m^{-3} (water), 0.95 µg m^{-3} (CMA) and 1.32 µg m^{-3} (2xCMA) over the median incDUST levels on control days. However, the application of CMA was statistically no more effective than water.

The phase 1 and phase 2 study periods were undertaken on tarmac road and show similar results despite the influence of demolition to the south during phase-1. The effect of water suppression was not significant on tarmac during either phase-1 or phase-2; in phase -1 a small decrease was measured and in phase-2 a small increase was detected. However, during both phases a significant decrease in incDUST was measured following the application of CMA relative to the control period. This was small in concentration terms; 1.99 µg m^{-3} as a mean for both phases. The double application of CMA was more effective than the single application; 3.11 µg m^{-3} as a mean for both phases. By reducing the increment to zero or below the CMA is effectively eliminating resuspension from the road.

During phase-3, increments of incDUST during the days when dust binders were applied were measured. However, median values for control days were very low (0.09 µg m^{-3}) reflecting the far reduced vehicle activity and consequently small amount of resuspension during this period; increments were not statistically significant.

Table 3: Median (1st quartile, 3rd quartile) of hourly increments of DUST for those weekdays without dust suppressor treatment (control) and when water, CMA or 2xCMA was applied. Only working hours were considered.

		Control	Water	CMA	2xCMA
All data	n	468	166	180	118
	incDUST (µg m^{-3})	1.26 (-1.11, 5.35)	0.54* (-0.97, 2.47)	0.31* (-0.87, 1.96)	-0.06* (-1.75, 3.34)
Phase I	n	185	39	45	27
	incDUST (µg m^{-3})	2.53 (-1.59, 17.51)	1.16 (-3.48, 11.36)	0.29* (-1.73, 2.68)	-1.35* (-16.51, 1.92)
Phase II	n	187	47	56	24
	incDUST (µg m^{-3})	1.69 (-0.65, 4.60)	2.23 (-0.68, 4.50)	-0.05* (-1.68, 2.74)	-0.67* (-1.62, 0.70)
Phase III	n	96	80	79	67
	incDUST (µg m^{-3})	0.09 (-0.79, 1.28)	-0.05 (-0.82, 0.93)	0.33 (-0.43, 0.89)	0.46 (-0.94, 5.28)

*** p<0.05 distribution statistically different from control.**

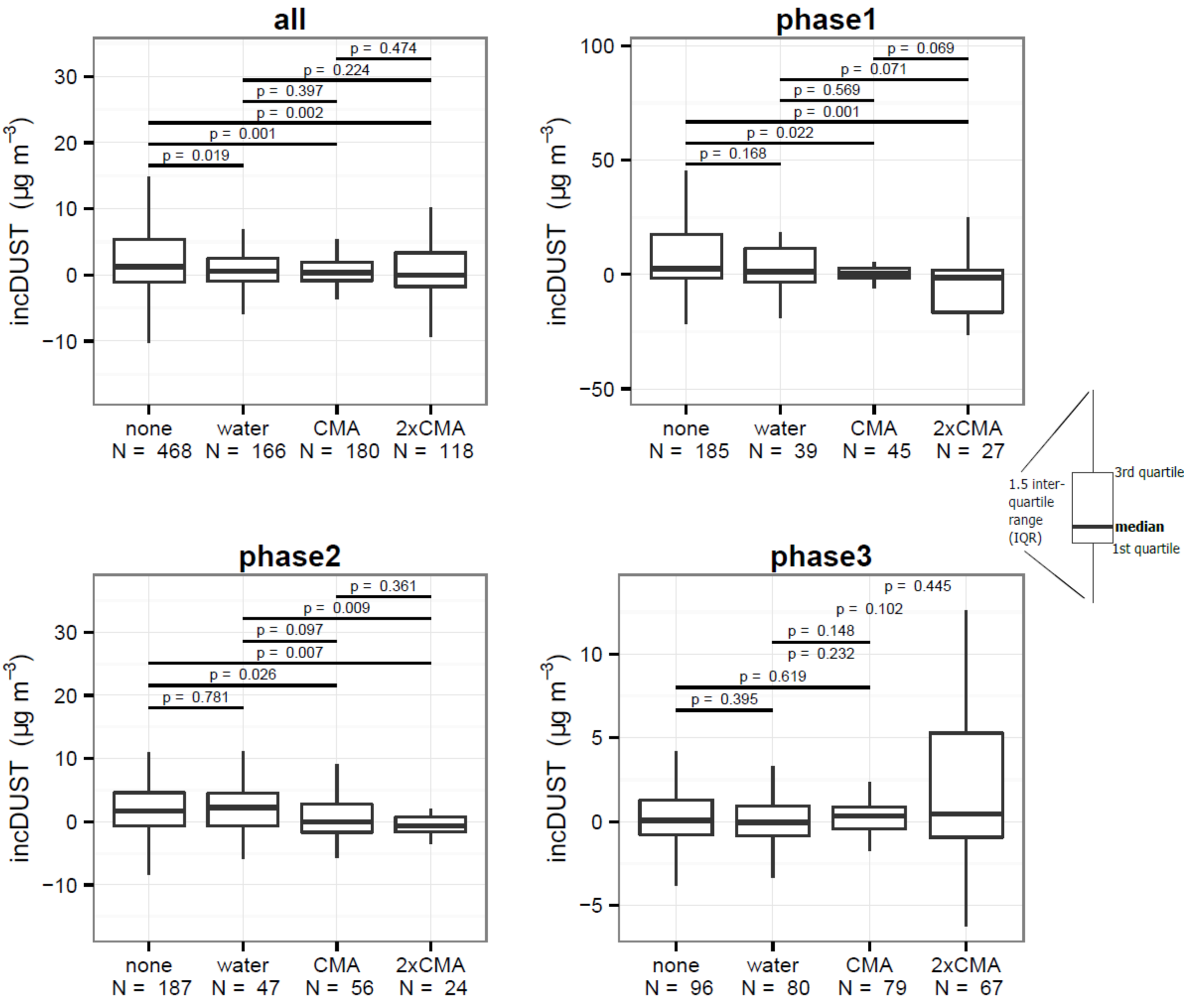


Figure 11: Boxplots of the mean hourly incDUST for those weekdays without treatment and for days when water, CMA and twice CMA was applied. p-values of the Kruskal-Wallis test of the different treatments compared to "control" are also shown. "*N*" indicates the number of available observations.

4.3.1. Impact of relative humidity

Due to the hygroscopic nature of coarse particles (Kassomenos et al., 2012), resuspension of particles is more difficult during wet conditions (high humidity values). This is illustrated during this study in Figure 10 where a high concentration of incDUST was observed following a decrease on the relative humidity. Furthermore, the median incDUST concentrations measured on control days were much lower on wet conditions (~0.8 µg m^{-3} for relative humidity > 70%) () compared to dry days (~2 µg m^{-3} for relative humidity < 70%). This is more accentuated in phase-1 when levels of incDUST were higher during dry conditions (4.2 µg m^{-3}) compared to wet conditions (0.3 µg m^{-3}).

To test whether the application of dust binders is worthwhile in wet conditions a Kruskal-Wallis test was applied to the hourly incDUST concentrations measured during hours when the relative humidity was higher than 70% (wet conditions) and lower than 70% (dry conditions). Overall, the application of CMA and 2xCMA still recorded statistically significant reductions of incDUST during wet conditions. However, water did not reduce the incDUST levels when ambient wet conditions. Examining the different phases could not draw out any further conclusions regarding the road surface type.

Table 4: Median (1st quartile, 3rd quartile) of hourly increments of DUST for those weekdays without dust suppressor treatment (control) and when water, CMA or 2xCMA was applied for dry conditions (relative humidity > 70%; wet ambient conditions). Only working hours were considered.

			Control	Water	CMA	2xCMA
All data	Wet	N	204	100	111	30
		incDUST (µg m^{-3})	0.81 (-0.76, 3.15)	0.58 (-0.70, 2.23)	-0.08* (-0.80, 1.32)	-0.11* (-0.62, 0.71)
	Dry	N	264	66	69	88
		incDUST (µg m^{-3})	1.98 (-1.58, 9.16)	0.31* (-2.39, 3.79)	0.75* (-2.11, 3.14)	-0.03* (-3.17, 5.06)
Phase 1	Wet	N	37	22	30	6
		incDUST (µg m^{-3})	0.27 (-1.51, 4.46)	1.06 (-0.32, 3.41)	0.19 (-0.67, 2.21)	-0.01 (-0.62, 0.78)
	Dry	N	148	17	15	21
		incDUST (µg m^{-3})	4.20 (-1.60, 19.64)	3.89 (-39.17, 12.75)	1.48 (-9.68, 5.10)	-7.30* (-19.26, 3.44)
Phase 2	Wet	N	104	27	37	
		incDUST (µg m^{-3})	2.13 (0.16, 4.70)	2.25 (1.36, 3.46)	0.24* (-1.07, 2.14)	0.62 (0.07, 1.53)
	Dry	N	83	20	19	18
		incDUST (µg m^{-3})	1.05 (-2.61, 4.31)	1.26 (-3.80, 8.85)	-0.24 (-11.15, 6.85)	-1.16 (-1.75, -0.15)
Phase 3	Wet	N	63	51	44	18
		incDUST (µg m^{-3})	-0.12 (-1.17, 0.87)	-0.09 (-0.77, 0.64)	-0.22 (-0.76, 0.44)	-0.22 (-0.78, 0.38)
	Dry	N	33	29	35	49
		incDUST (µg m^{-3})	0.67 (-0.33, 3.02)	0.02 (-1.06, 1.29)	0.80 (0.32, 1.77)	2.28 (-1.68, 6.38)

4.3.2. Impact of traffic flows

Dust resuspension is clearly influenced by the amount of traffic as well at meteorological conditions; this is demonstrated in Figure 8 where the incDUST concentrations rose during the day and by the low concentrations during phase 3 when the traffic was at its lowest. However, Figure 12 shows that the amount of traffic (as measured by vehicle logged in at the gate) is not related to the incDUST measured. This may be because the logged vehicles do not accurately represent the number of vehicles travelling past the measurement site.

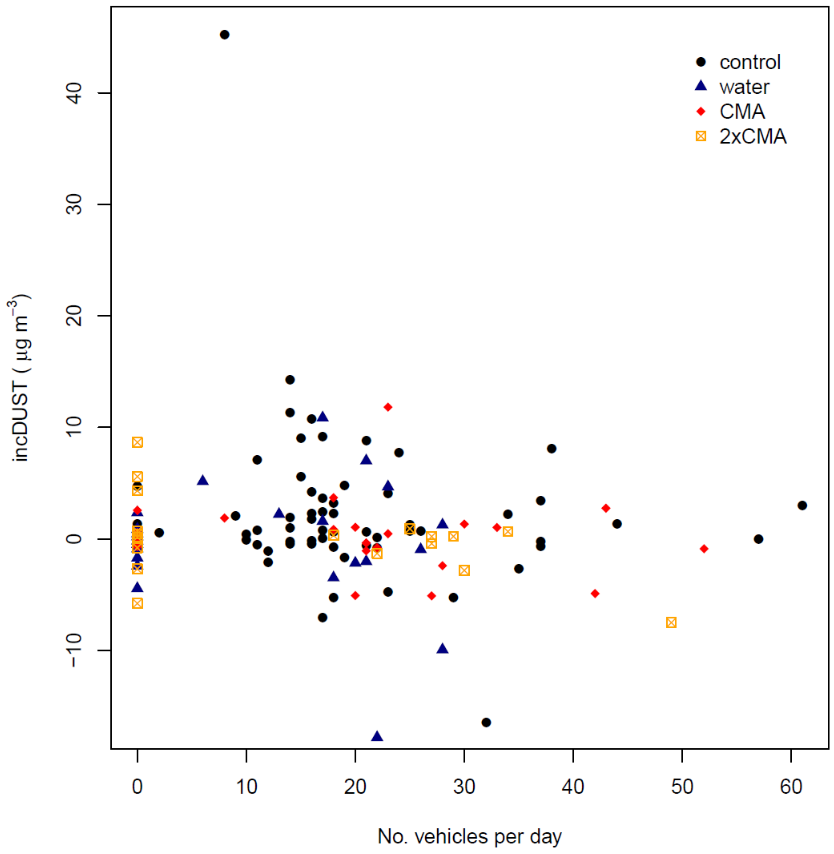


Figure 12: Mean daily increments of DUST vs the number of daily vehicles using the haulage road in the Heygate construction site.

5. Discussion and conclusions

In this study the effectiveness in the reduction of dust levels associated with the passage of vehicles when applying water and CMA (once and twice daily) within a haulage road at the Heygate construction site. Dust concentrations were continuously measured by an Osiris dust monitor at two monitoring sites located by the sides of a haulage road separated by 10 meters. Dust concentrations due to vehicle passage were calculated for specific wind conditions when upwind-downwind pairs could be defined. The study period lasted 11 months, from April 2014 to March 2015, and three differentiated phases were defined based on the conditions of the road: phase-1 (April-July 2014) and phase-2 (July-December 2014) the surface of the road was tarmac but phase-1 was characterized by demolition activities in the vicinities of the monitoring sites; in phase-3 (Jan-Mar 2015) the surface of the road was unmade.

It was clear from the ambient measurements that construction activities are a source of dust to the atmosphere. The monitoring sites located in the haulage road registered a larger number of daily exceedences (daily means > 50 µg m^{-3}) compared to the urban background locations. The monitors recorded between 12 to 16 daily exceedences while the urban background site did not register any for the same period of time. The exceedences days took place only during working days (Monday to Friday).

The application of dust binders to the haulage road effectively reduced the dust levels by 0.72 µg m^{-3} (water), 0.95 µg m^{-3} (CMA) and 1.32 µg m^{-3} (2xCMA) over the median incDUST levels on control days. The largest reductions of dust were attained by 2xCMA, however, the three methods were not statistically different. Examining the concentrations, the application of CMA and 2xCMA effectively removed the resuspension of dust from the road.

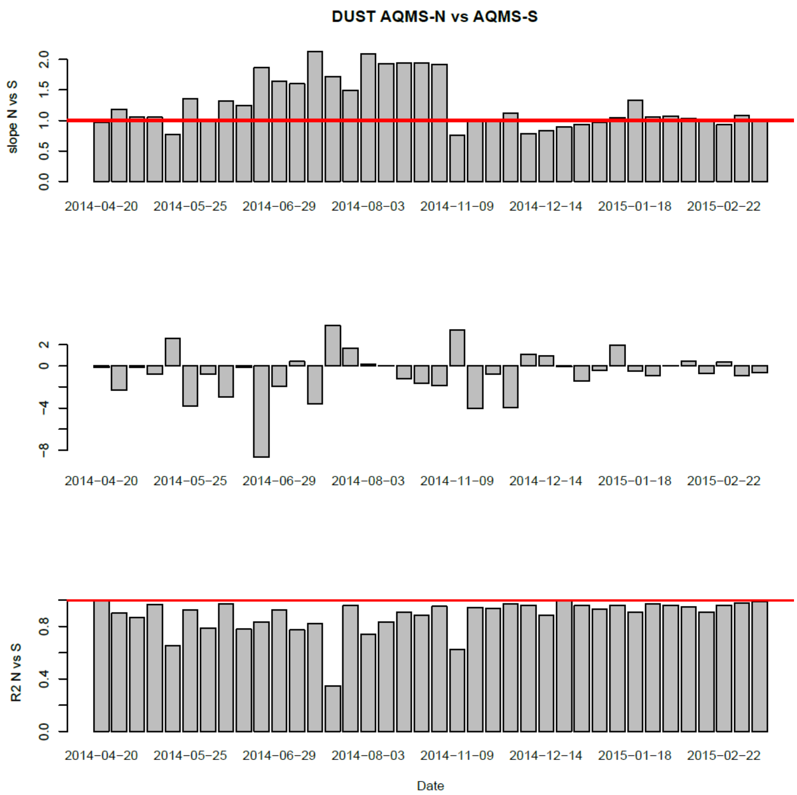
During phase-1 and phase-2, when the road was tarmac, CMA and 2xCMA reduced the levels of dust but there was no statistical difference between the two methods. In phase-3, none of the methods reduced the levels of dust from the road. This is explained by the very low concentrations measured by the road during control days.

During dry ambient conditions, the three methods registered statistically significant reductions of dust from the road: 84% (water), 62% (CMA) and 99% (2xCMA). The three methods were not statistically different. However, during wet ambient conditions (defined by the times when the relative humidity > 70%), only CMA and 2xCMA (and not water) effectively reduced the levels of dust from the road. This suggests that it is not worth applying water in ambient conditions where RH >70% but it is worth applying CMA.

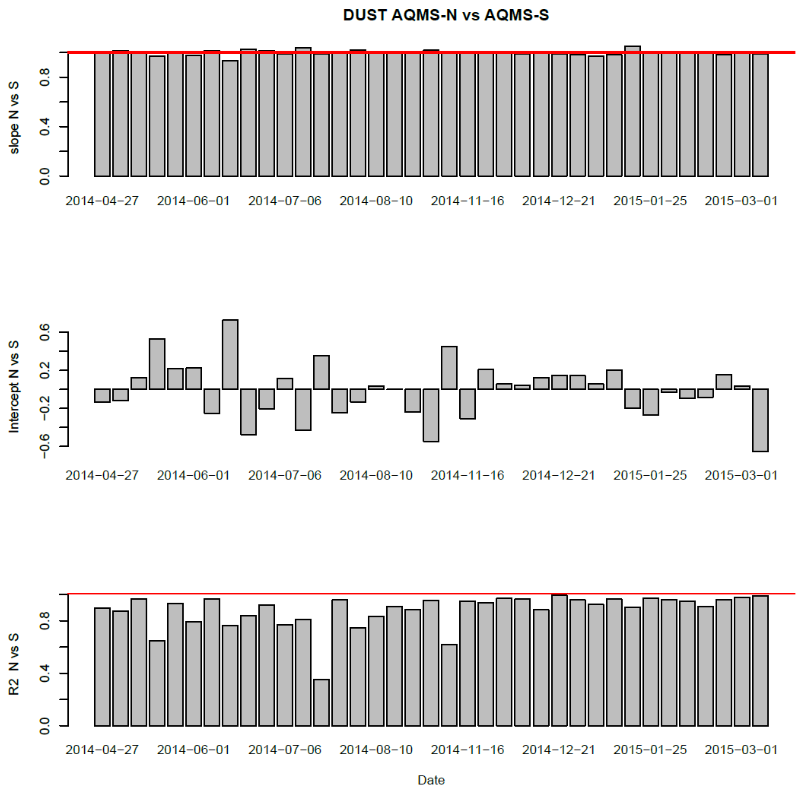
This study clearly adds significantly to the evidence base relating the use of water and dust binders for supressing resuspension and provides useful information for formulating best practice guidance. Any future studies should seek to target roads with a higher throughput of vehicles and make a more accurate assessment of the vehicle passing the measurement site by using an automatic traffic counting system.

6. Appendix A. Correction for drift

As shown in Figure 5, dust concentrations from both AQMS-N and AQMS-S were very similar on Sundays due to lack of construction activity. In order to correct for drift that instruments experienced, a correction was applied. Hourly measurements of dust at AQMS-N were compared to those measured at AQMS-S on Sundays and a time series of slope and offset were obtained by means of Reduced-Major-Axis (RMA) regression. From Figure Appendix Figure A. 2 is evident that instruments experienced drift along the time series. From the RMA regressions, a scaling factor and offset was applied to scale the AQMS-N dust data against AQMS-S. Scaled data is represented in Figure Appendix Figure A. 2 and a better correlation was obtained.



Appendix Figure A. 1.Time series of the slope, offset and determination coefficient for the hourly comparison of dust concentrations measured at AQMS-N vs AQMS-S on Sundays. Reduced-Major-Axis (RMA) regressions were used.



Appendix Figure A. 2. Time series of the slope, offset and determination coefficient for the hourly comparison of scaled dust concentrations measured at AQMS-N vs AQMS-S on Sundays. Reduced-Major-Axis (RMA) regressions were used.

7. Appendix B. Time log when dust binders were applied

Appendix Table B. 1. Time log (expressed on local time) when dust abatement measures were applied to Deacon Way in the Heygate construction site.

Phase	Date	Dust suppressant	Start time	End time
Phase I	28/04/2014	water	7:00	7:40
	29/04/2014	water	7:20	7:35
	30/04/2014	water	7:50	8:02
	02/05/2014	water	7:00	7:15
	06/05/2014	CMA	7:00	7:20
	08/05/2014	CMA	7:00	7:15
	09/05/2014	CMA	7:00	7:15
	12/05/2014	2XCMA	7:00; 12:15	7:20; 12:30
	13/05/2014	2X CMA	7:15; 12:15	7:30; 12:30
	14/05/2014	2X CMA	7:20; 13:30	7:40; 13:50
	15/05/2014	2X CMA	7:05; 13:05	7:15; 13:20
	16/05/2014	2X CMA	7:00; 13:15	7:15; 13:30
	19/05/2014	water	7:15	7:30
	20/05/2014	water	6:55	7:10
	21/05/2014	water	6:45	7:00
	22/05/2014	water	6:30	6:45
	23/05/2014	water	6:30	6:47
	27/05/2014	CMA	6:45	7:00
	28/05/2014	CMA	7:00	7:15
	29/05/2014	CMA	6:30	6:45
	30/05/2014	CMA	6:30	6:45
Phase II	07/07/2014	water	7:00	7:15
	08/07/2014	water	6:40	7:00
	09/07/2014	water	7:00	7:15
	10/07/2014	water	6:45	7:00
	11/07/2014	water	6:45	7:00
	14/07/2014	CMA	6:50	7:05
	15/07/2014	CMA	6:45	7:00
	16/07/2014	CMA	6:50	7:05
	17/07/2014	CMA	6:25	6:40
	18/07/2014	CMA	6:50	7:00
	21/07/2014	2xCMA	6:45; 13:20	7:0; 13:35
	22/07/2014	2xCMA	6:55; 13:00	7:10; 13:55
	23/07/2014	2xCMA	6:50; 12:00	7:05; 12:15
	24/07/2014	2xCMA	6:15; 12:45	6:30; 13:00
	25/07/2014	2xCMA	6:45; 12:40	7:00; 12:55
	28/07/2014	water	6:40	6:50
	29/07/2014	water	6:50	7:05
	30/07/2014	water	7:00	7:15
	31/07/2014	water	6:45	7:00
	01/08/2014	water	6:45	7:00
	04/08/2014	water	7:00	7:10
	05/08/2014	water	n/a	n/a

	06/08/2014	water	6:45	7:00
	01/12/2014	CMA	6:00	6:20
	02/12/2014	CMA	6:00	6:15
	03/12/2014	CMA	6:00	6:15
	04/12/2014	CMA	6:00	6:15
	05/12/2014	CMA	6:00	6:15
	08/12/2014	2xCMA	7:00; 13:20	7:15; 13:35
	09/12/2014	2xCMA	6:00; 13:00	6:20; 13:20
	10/12/2014	2xCMA	6:00; 10:50	6:15; 11:05
	11/12/2014	2xCMA	6:00; 13:10	6:15; 13:25
	12/12/2014	2xCMA	5:55; 12:35	6:10; 12:50
Phase III	26/01/2015	water	6:00	06:15
	27/01/2015	water	6:00	06:20
	28/01/2015	water	6:00	06:30
	29/01/2015	water	6:00	06:20
	30/01/2015	water	6:30	06:45
	02/02/2015	CMA	6:20	06:40
	03/02/2015	CMA	7:45	08:10
	04/02/2015	CMA	6:00	06:15
	05/02/2015	CMA	6:00	06:20
	06/02/2015	CMA	6:00	06:15
	09/02/2015	2xCMA	6:00; 11:50	6:15; 12:15
	10/02/2015	2xCMA	6:00; 12:00	6:25; 12:20
	11/02/2015	2xCMA	6:10; 12:50	6:25; 13:10
	12/02/2015	2xCMA	7:30; 12:45	7:40; 13:00
	13/02/2015	2xCMA	6:00; 13:15	6:15; 13:25
	16/02/2015	water	6:00	6:15
	17/02/2015	water	5:50	6:05
	18/02/2015	water	5:50	6:10
	19/02/2015	water	6:50	7:05
	20/02/2015	water	7:00	7:15
	23/02/2015	CMA	6:50	7:05
	24/02/2015	CMA	6:00	n/a
	25/02/2015	CMA	6:00	6:15
	26/02/2015	CMA	6:00	6:15
	02/03/2015	2xCMA	5:40; 12:00	5:55; 12:15
	03/03/2015	2xCMA	5:45; 12:15	6:00; 12:25
	04/03/2015	2xCMA	6:10; 07:12	6:30; 10:48
	05/03/2015	2xCMA	5:40; 13:12	5:55; 02:24
	06/03/2015	2xCMA	5:45; 7:12	6:00; 10:48