

# Long-Term Efficiencies of Dust Suppressants to Reduce PM<sub>10</sub> Emissions from Unpaved Roads

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## ABSTRACT

A 14-month study was undertaken to assess the long-term efficiencies of four dust suppressants (i.e., biocatalyst stabilizer, polymer emulsion, petroleum emulsion with polymer, and nonhazardous crude-oil-containing materials) to reduce the emission of PM<sub>10</sub> from public unpaved roads. PM<sub>10</sub> emission rates were calculated for each test section and for an untreated section for comparison purposes. Emission rates were determined from PM<sub>10</sub> concentrations measured from 1.25 m to 9 m upwind and downwind of the road and above its surface. Calculated emission factors ranged between zero and 1,361 g-PM<sub>10</sub>/vehicle kilometer traveled (VKT) (average uncertainty = ±35 g-PM<sub>10</sub>/VKT) for the four types applied. One week after application, suppressant efficiencies ranged between 33% and 100% for the four types applied. After 8–12 months of exposure to weathering and 4,900–6,400 vehicle passes, the suppressant efficiencies ranged from zero to 95%. Roadway surface properties associated with low-emitting, well-suppressed surfaces are (1) surface silt loading and (2) strength and flexibility of suppressant material as a surface layer or cover. Suppressants that create surface conditions resistant to brittle failure are less prone to deterioration and more likely to increase long-term reduction efficiency for PM<sub>10</sub> emissions on unpaved roads.

## IMPLICATIONS

PM<sub>10</sub> emissions from unpaved roads constitute large fractions of emission inventories. Chemical suppressants often are recommended to reduce these emissions, but the effectiveness of these measures over time has not been proven. This study shows that several suppressants do not stand up to long-term wear and tear from vehicles and weather. Treatments that resist brittle failure of the surface have the greatest potential to create long-term dust reductions. Inexpensive surface property measurements can be applied to establish quantitative performance standards for suppressant acceptability.

## INTRODUCTION

Fugitive dust consists of geological material that is injected into the atmosphere by natural wind blowing across disturbed and undisturbed land surfaces and by vehicle-related activities on paved roads, unpaved roads, agricultural fields, and construction sites. The main chemical constituents of these particles are oxides of silicon, aluminum, and iron and some calcium compounds. Most of the suspended dust is deposited within a short distance of its origin, yet a portion of it can be transported long distances by wind.<sup>1</sup> These suspended particles have been shown to constitute a large fraction of PM<sub>10</sub> (particles with aerodynamic diameters less than 10 micrometers)<sup>2</sup> in many urban and nonurban areas, including California's San Joaquin Valley (SJV).<sup>3,4</sup> Of the estimated  $3.4 \times 10^5$  kg/day of PM<sub>10</sub> fugitive dust emitted within the SJV,  $1 \times 10^5$  kg/day is estimated to derive from unpaved roads emissions, and  $0.5 \times 10^5$  kg/day is from paved roads.<sup>5</sup>

Unpaved roads consist of a graded and compacted roadbed that is usually created from soil material present at the site. Well-constructed unpaved roads may be finished by topping with a hard surface material such as gravel or crushed rock, but this is not always the case. The forces created by the rolling wheels of vehicles remove fine particles from the roadbed and also pulverize aggregates lying on the surface. Dust is ejected into the air by the shearing force of the tires and by the turbulent vehicle wakes.<sup>6</sup> Dust emission rates have been found to depend on the fine particle content of the road,<sup>7</sup> soil moisture content, roadbed load capacity,<sup>8</sup> and vehicle speed.<sup>6</sup> Empirically derived particulate emission factors contain exponential relationships of dust emissions to vehicle weight and number of wheels.<sup>9</sup>

The effectiveness of control methods for reducing dust emissions from unpaved roads has not been well-measured or documented. Beggs<sup>10</sup> examined several fugitive dust control method demonstration projects and found that many of them were poorly designed and yielded

inconclusive results. Even when studies were well-designed, the benefits of the control application for air quality often were undetectable, because the control methods being applied had not been understood or correctly implemented. Control method demonstration studies are difficult to design, because the mechanics of particle resuspension from road surfaces is still poorly understood. Road surface properties that influence  $PM_{10}$  emissions need to be better identified and quantified. The role of vehicle type, size, weight, shape, and speed in affecting the magnitude of emissions from road surfaces also requires further investigation. Several suppressant effectiveness studies for unpaved roads in industrial sites are reviewed in a U.S. Environmental Protection Agency (EPA) document.<sup>11</sup> The unpaved road dust control demonstration study reported here intends to (1) evaluate  $PM_{10}$  dust emissions from unpaved roads in California's SJV for different suppressant materials, (2) determine the long-term efficiency of suppressants under typical vehicle load and weather conditions, and (3) develop performance specifications for dust suppressant materials that are useful for regulating these emissions. Complete study details and the data acquired are presented by Watson et al.<sup>12</sup>

## EXPERIMENTAL METHODS

### Suppressant Selection and Application

Watson et al.<sup>12</sup> reviewed more than 60 commercial suppressants in the categories of salts, asphalt/petroleum emulsions, tree resin and organic emulsions, lignin sulfonates, polymers, fibers and mulches, and proprietary formulations. Proposals from suppressant manufacturers and vendors were solicited and evaluated to select roadway treatments that (1) represent a variety of modern products meeting applicable toxicity and volatile organic compounds (VOC) criteria for public roads, (2) minimize cost of materials and applications, and (3) represent a variety of logistical requirements and application methods. The suppressants selected for testing were: (1) biocatalyst stabilizer (BS) (EMC<sup>2</sup>, Soil Stabilization Products Company, Inc., Merced, CA), (2) polymer emulsion (PE) (Soil Sement, Midwest Industrial Supply, Inc., Canton OH), (3) petroleum emulsion with polymer (PEP) (Coherex PM, Reed and Graham, Inc., Sacramento, CA), and (4) nonhazardous crude-oil-containing materials (NHCO) (Western States Petroleum Association, Glendale, CA).

EMC<sup>2</sup> is a biocatalyst that intends to improve the cementation and stability of

compacted aggregate and earth materials. Soil Sement, the PE, creates a pliable surface film that seals the underlying road material. Coherex PM bonds the road material causing agglomeration of fines and, with the addition of the polymer material, forms a surface crust. The NHCO, a byproduct of the oil extraction industry, is mixed with aggregate and cures to a hard, but still pliable, surface of cemented aggregates.

Fields Road, located in Merced County, CA, (see Figure 1) was selected as a test site, because it possessed a straight length of three kilometers, an east-west direction so the dominant valley winds would be perpendicular to the road, and relatively level topography. It also had moderate traffic from light-duty vehicles, typical of many unpaved public roads in the SJV. The road was graded and crowned by the Merced County Department of Public Works one week prior to suppressant application, in accordance with the department's standard unpaved road maintenance practices. One test section approximately 500 m in length was assigned to each suppressant, and the suppressants were applied by each supplier according to their standard procedures.

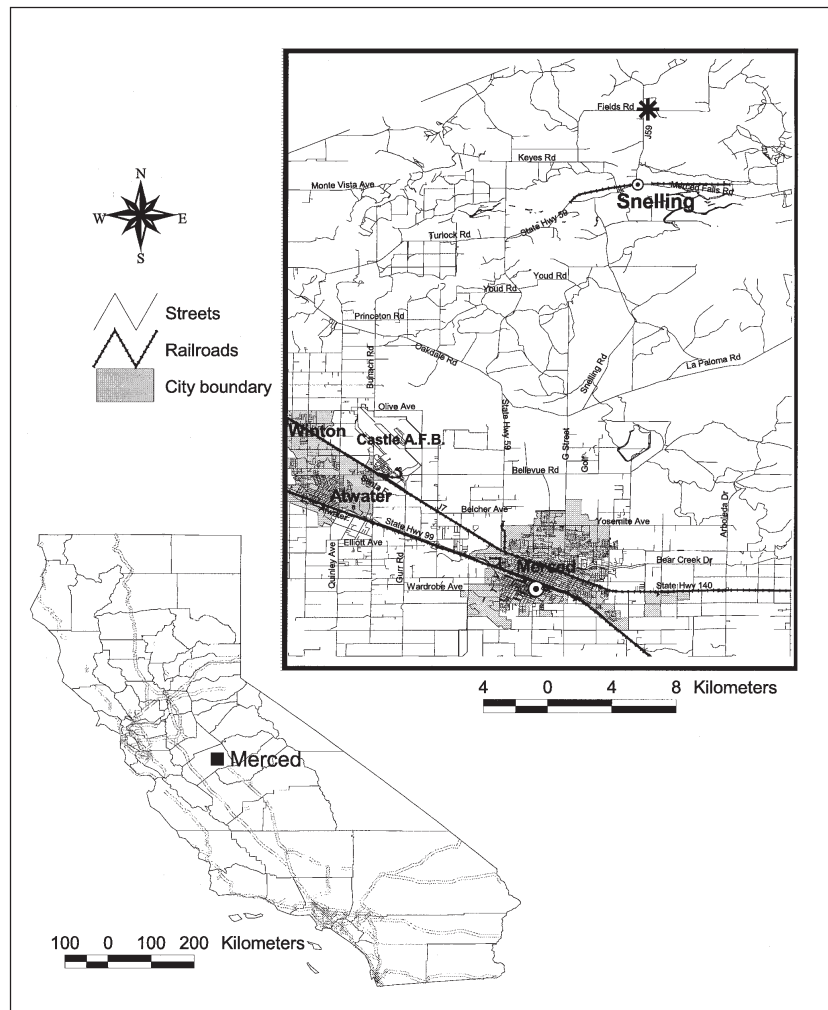


Figure 1. Location of Fields Road in Merced County, CA.

The application of the BS suppressant involved scarifying the unpaved road surface with a grader, mixing the suppressant material with the soil, followed by wetting, a second topical application, grading, and finally rolling. For the PE suppressant, the surface was wetted, sprayed with a dilute solution, and then finished with a more concentrated topical application. The PEP application involved additional grading, wetting of the surface, and a topical application of the suppressant material. For the NHCO suppressant, the section was graded, followed by the application of the aggregate-NHCO mixture brought to the site by bottom-dumping trucks, and subsequently graded and rolled.

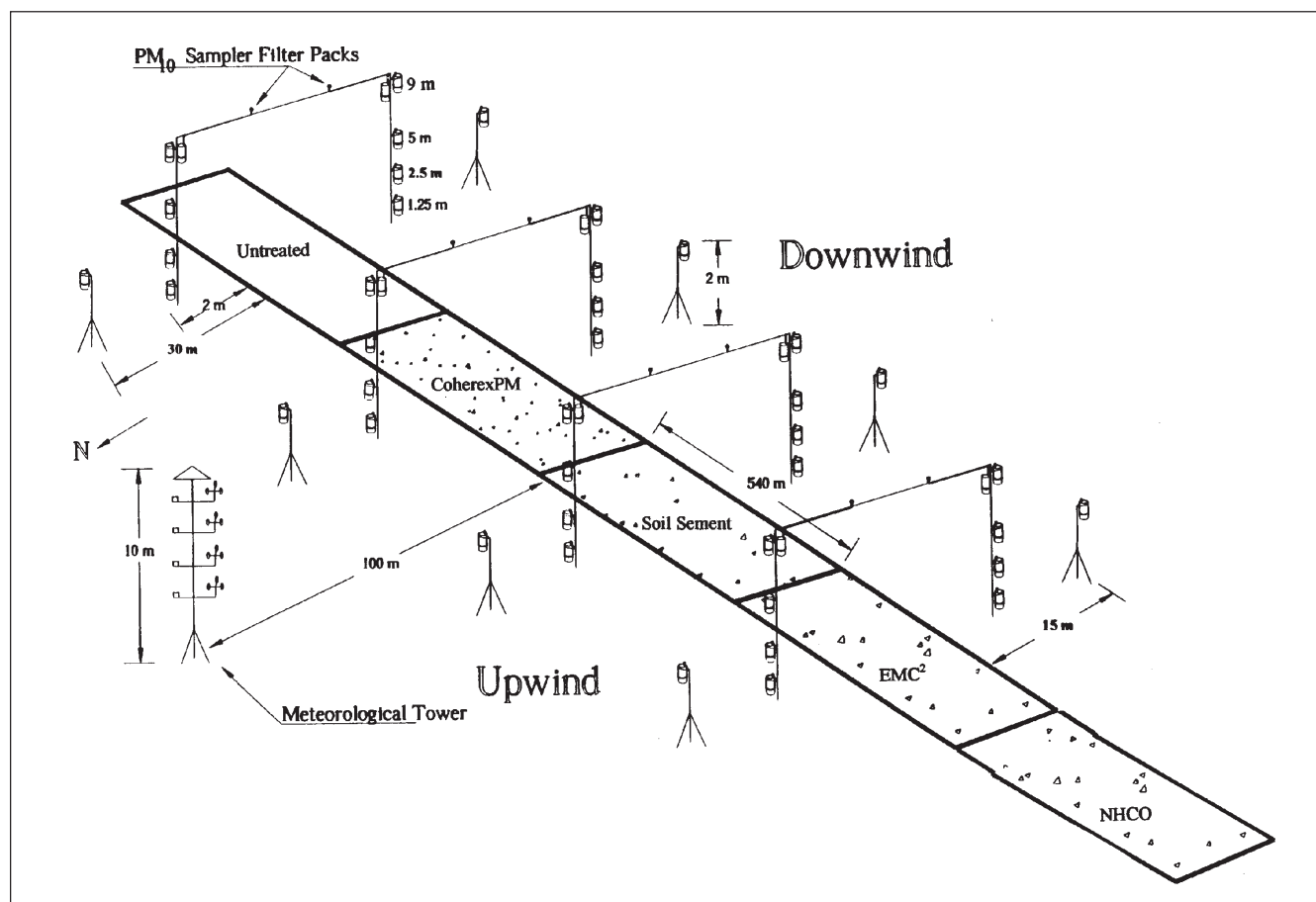
The BS, PE, and PEP suppressants were applied to Fields Road during July 13–18, 1995, and the NHCO was applied during October 17–19, 1995. A fifth section was left untreated for comparison of  $PM_{10}$  emissions with those from the treated sections.

### $PM_{10}$ Sampling

$PM_{10}$  was measured upwind and downwind of each test section with tower-mounted battery-powered MiniVol  $PM_{10}$  samplers (AIRMETRICS, Springfield, OR). MiniVol samplers have been deployed in several previous studies<sup>13–16</sup> and have shown good comparability to collocated  $PM_{10}$

reference samplers when properly operated. The same sampling protocol that was used by Chow et al.<sup>13</sup> for MiniVol samplers deployed in the relatively dusty environment of the southern Imperial Valley, CA, was used in this study. Chow et al.<sup>13</sup> reported a regression slope of  $1.05 \pm 0.03$  with a correlation coefficient of 0.98 for 62 paired concentration values for MiniVol and the Sierra-Andersen 254 medium volume  $PM_{10}$  samplers (Equivalence Reference Number RFPS-0389-071). The MiniVol uses a rechargeable battery pack to power a pump that draws ambient air through a greased  $PM_{10}$  impactor inlet and through a preweighed Teflon-membrane filter (Zeflour PTFE 47mm, Gelman Sciences, Ann Arbor, MI) at a 5 L/min flow rate. The network configuration used on Fields Road is shown in Figure 2.

Each test segment was equipped with a sampler array located at or near its midpoint, to minimize the effects of suppressant material tracked in from adjoining test sections. Twelve samplers were deployed in each test section to measure  $PM_{10}$  emissions from the road. The 12-sampler array allowed for sampling when the wind was predominantly from the north or the south, which historical meteorological records indicated as the dominant wind directions for this area. This sampling array minimized



**Figure 2.** Location of MiniVol  $PM_{10}$  samplers and meteorological tower in relation to roadway test sections.

the chance of a missed sampling day. Four samplers, located at heights of 1.25 m, 2.5 m, 5 m, and 9 m above ground level (AGL), characterized the vertical ambient PM<sub>10</sub> concentration profile exiting a test section. An upwind sampler at 2 m AGL was placed 30 m from each test section to ensure a background sample was obtained that was unaffected by any roadway emissions. Another sampler at 2 m AGL was located 15 m downwind of each test section to estimate PM<sub>10</sub> attenuation with distance. Two additional samples were taken at a height of 9 m, 3 m from each sampler tower, directly over each section to characterize PM<sub>10</sub> that might leave the road via vertical dispersion. With this array, a mass balance of PM<sub>10</sub> entering and leaving the boundaries of the sampling towers can be determined.

### Meteorological Measurements

A meteorological tower ~100 m north of Fields Road was instrumented as follows: four-cup anemometers (Met One, Model 014, Grants Pass, OR) at 1.25 m, 2.5 m, 5 m, and 9 m height to characterize the wind speed profile; two wind vanes (Met One, Model 024, Grants Pass, OR) at 1.25 m and 9 m height to monitor wind direction; and one temperature and relative humidity sensor at 5 m height (CSI 207, Campbell Scientific, Logan, UT). Average wind speeds and the angle at which the wind approached the road are required to calculate PM<sub>10</sub> emission rate from each test surface. Fifteen-minute averages were recorded for each meteorological variable during each test.

### Surface Characterization Measurements

Roadway surface properties were measured on July 21, September 22, October 21, and December 28, 1995, and on March 26, June 15, July 15, and August 23, 1996, to determine how they changed as a result of traffic and weather. These included bulk surface loading, suspendable dust (silt, particles <75 μm geometric diameter) loading, aggregate size distributions, moisture content, and surface strength.

Loose surface material on Fields Road was collected by sweeping with a fine-bristled brush and a collection pan from two 0.3 m × 10 m strips across the width of the road surface in each test section. The bulk surface loading of

loose material was estimated by dividing the mass of the collected material by the area from which the sample was removed. Subsamples were later prepared using a sample-splitter (Soiltest CL-280, ELE International, Inc., Lake Bluff, IL) that divides soil samples into two equal portions to determine silt content and aggregate size distributions following the methodologies of Cowherd et al.<sup>7</sup> A small knife-blade was used to remove soil material from the top few millimeters of the road for moisture content analysis. Moisture content was determined by the difference in weight before and after oven drying at 105 °C.

A penetrometer (Soiltest Proctor Penetrometer, ELE International, Inc., Lake Bluff, IL) that measures unconfined compression strength (N/cm<sup>2</sup>) was applied across each test section to determine surface strength. The penetrometer applies an increasing pressure on the surface until the probe penetrates the surface to a depth of 12.7 mm or induces brittle failure. On average, 40 measurements of the surface strength were taken at 0.25 m intervals across the width of each test section, at two locations in each section. This measurement is similar to, but not an exact replication of, the modulus of rupture test used by Gillette et al.<sup>17</sup> to assess the strength of desert soil crusts.

### Emissions Tests

Emission tests were conducted at the Fields Road site on July 22–27, 1995, October 17–22, 1995, and June 13–18, 1996 (see Table 1). Between July 1995 and October 1995

**Table 1.** Dates, times, durations, and average meteorological conditions for each emissions test.

Date	Time	Duration (min)	Average 10 meter		Average 5 meter	
			Wind Speed (m/sec)	Wind Direction (°)	Temperature (°C)	Relative Humidity (%)
7/22/95	8:00–14:00	360	6.3	302	25	46
7/23/95	8:00–14:00	360	5.0	298	25	48
7/24/95	8:00–14:00	360	4.7	299	26	47
7/25/95	8:00–14:00	360	4.2	300	26	45
7/26/95	8:00–14:00	360	3.4	298	30	31
7/27/95	8:00–14:00	360	2.9	216	35	23
10/17/95	8:00–14:00	360	2.4	182	22	55
10/18/95	8:00–14:00	360	2.5	280	23	50
10/20/95	8:00–14:00	360	2.4	235	25	41
10/21/95	8:00–14:00	360	4.8	309	22	45
10/22/95	8:00–14:00	360	2.8	243	16	32
6/13/96	9:00–15:00	360	2.7	249	30	28
6/14/96	9:00–15:00	360	4.9	300	26	29
6/15/96	9:00–15:00	360	3.7	284	27	28
6/16/96	9:00–15:00	360	3.6	284	26	38
6/17/96	9:00–15:00	360	3.4	282	25	41
6/18/96	9:00–15:00	360	4.7	295	23	34

the weather remained dry and there were moderate traffic levels (17 vehicles/day). During the period between December 1995 and June 1996, heavier than average precipitation was recorded in the area, although daily average traffic volume was similar to the July to October period.

PM<sub>10</sub> emissions from the test sections were created by a 3/4-ton pick-up truck traveling back and forth along the roadway for 100 passes over each six-hour sampling interval. Constant vehicle speeds of 40 km/hr and 55 km/hr were maintained and alternated from day to day. The number of vehicle passes during and between each sampling period was determined with a pneumatic traffic counter. Vehicle kilometers traveled (VKT) from local traffic recorded by the counter during each measurement period were included with the VKT of the pick-up truck.

## RESULTS

### Emission Rates

The measured background PM<sub>10</sub> concentration associated with each test section and measurement interval was determined from the 2-m AGL sampler located upwind of each test section. This background concentration was subtracted from each PM<sub>10</sub> measurement on the tower and assumes that the upwind vertical mass concentration profile was in equilibrium.<sup>18</sup> Background concentrations of PM<sub>10</sub> averaged 31.8 ± 12.8 µg/m<sup>3</sup> in July 1995, 73.5 ± 52 µg/m<sup>3</sup> in October 1995, and 25.3 ± 11.1 µg/m<sup>3</sup> in June 1996.

The precision of an individual PM<sub>10</sub> concentration measurement was calculated based upon propagation of an assumed error of 5% for the sample volume, and the error associated with replicate weighing of 100% of the filters before exposure and 30% of the filters after exposure. The average propagated precision of an individual PM<sub>10</sub> measurement for mass concentrations ≤100 µg/m<sup>3</sup> was 6.5 µg/m<sup>3</sup> and for mass concentrations ≥100 µg/m<sup>3</sup> was 14.5 µg/m<sup>3</sup>.

The mass of particles leaving the roadway was calculated by summing over six different flux planes through which particles might pass. The flux plane dimensions are shown in Figure 3. The PM<sub>10</sub> concentration in each flux plane was represented by the MiniVol measurement. The PM<sub>10</sub> emission factor can be expressed as:

$$E = \frac{TL}{D} \sum_1^n C_i V_i \Delta h_i \quad (1)$$

where  $E$  = the flux per unit vehicle kilometer traveled (g-PM<sub>10</sub>/VKT);  $T$  = the duration of the test (sec);  $L$  = flux plane length (541 m);  $D$  = the total vehicle distance traveled in a test section (km);  $n$  = the flux plane number;  $C_i$  = average

flux plane concentration from corresponding MiniVol sampler ( $i = 1$  to 6) (µg/m<sup>3</sup>);  $V_i$  = average wind speed perpendicular to flux plane  $i$  (m/sec); and  $\Delta h_i$  = height increment of flux plane  $i$  (m) (see Figure 3).

This flux equation assumes the following:

- (1) The point measurement of PM<sub>10</sub> mass concentration represents the average concentration in the entire flux plane.
- (2) Measured PM<sub>10</sub> concentrations were attributed to roadway emissions only when differences between downwind and upwind (background) PM<sub>10</sub> measurements exceeded propagated precisions (~15 µg/m<sup>3</sup>). When PM<sub>10</sub> measured in the samples taken over the road exceeded background PM<sub>10</sub> concentrations by the propagated precisions, flux planes 5 and 6 from Figure 3 were added to the summation procedure of eq 1. If the differences between a downwind and upwind (background) PM<sub>10</sub> measurement was less than the propagated precision, the flux plane concentration was set to zero.
- (3) Wind speed and direction measured at the meteorological tower represented these variables across the entire 3 km length of Fields Road test sections, and the average perpendicular wind speed across the flux plane did not significantly differ from point-specific wind speeds within each flux plane. Fifteen-minute average wind speeds were multiplied by the cosine of the angle between the wind direction and the road to determine the perpendicular velocity component.  $V_i$  is constant for flux planes 5 and 6 and equivalent to the regional friction speed,  $u_*$  (m/sec). The friction speed,  $u_*$ , was calculated from the mean wind speed versus the logarithm of height relationship by least squares fit of the data to the Prandtl equation:<sup>19</sup>

$$\frac{u_z}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_0} \right) \quad (2)$$

where  $u_z$  = wind speed at height  $z$  (m/sec);  $u_*$  = friction speed (m/sec);  $\kappa$  = von Karman's constant (≈0.4);  $z$  = reference height of wind speed measurement (m); and  $z_0$  = roughness length (m).

This equation describes the semi-logarithmic form of the wind speed profile in the vertical dimension within the lower 100 m of the atmospheric surface layer in neutral stability conditions where there are no large roughness elements. The friction speed approximates the vertical wind speed component and, for each sampling period, was of sufficient magnitude to move a 10 µm (aerodynamic) diameter particle upwards.<sup>20</sup>

**Table 2.** PM<sub>10</sub> emission factors at 40 km/hr and 55 km/hr for each test during the three intensive monitoring periods.

Date	Vehicle Speed (km/hr)	Emission Factors (g-PM <sub>10</sub> /VKT)				
		Untreated	BS <sup>a</sup>	PEP <sup>b</sup>	PE <sup>c</sup>	NHCO <sup>d</sup>
7/22/95	40	470	205	0	0	N/A
7/24/95	40	428	343	0	71	
7/26/95	40	800	508	11	60	
(Average)		566	352	4	44	
(Std.Dev.)		204	152	6	38	
7/23/95	55	954	478	0	58	
7/25/95	55	962	508	7	0	
7/27/95	55	347	393	20	11	
(Average)		754	460	9	23	
(Std.Dev.)		353	60	10	31	
10/17/95	40	475	461	128	16	N/A
10/20/95	40	364	393	121	33	
10/22/95	40	307	448	119	17	
(Average)		382	434	123	22	
(Std.Dev.)		85	36	5	10	
10/18/95	55	243	268	65	1	
10/21/95	55	1471	924	237	0	
(Average)		857	596	151	0.5	
(Std.Dev.)		868	464	122	1	
6/13/96	40	189	155	67	19	32
6/15/96	40	190	250	86	24	4
6/17/96	40	122	147	71	17	14
(Average)		167	184	75	20	17
(Std.Dev.)		39	57	10	4	14
6/14/96	55	751	1361	427	83	64
6/16/96	55	300	526	189	68	9
6/18/96	55	516	697	254	82	20
(Average)		522	861	290	78	31
(Std.Dev.)		226	441	123	8	29

<sup>a</sup>Biocatalyst stabilizer (EMC<sup>2</sup>, Soil Stabilization Products).

<sup>b</sup>Petroleum emulsion with polymer (CoherexPM, Reed-Graham).

<sup>c</sup>Polymer emulsion (Soil Sement, Mid-West Ind. Supply).

<sup>d</sup>Non-hazardous-crude-oil mixture (WSPA).

Table 2 shows PM<sub>10</sub> emission factors for each test conducted during the sampling periods (a sample calculation and estimation of emission factor uncertainty is shown in Appendix 1). One week after suppressant treatment, the calculated emission factors ranged from zero ( $\pm 34$ ) g-PM<sub>10</sub>/VKT for the PE and PEP sections to 960 ( $\pm 57$ ) g-PM<sub>10</sub>/VKT for the untreated section. The untreated and BS test sections produced the highest PM<sub>10</sub> emissions

after minimal wear and tear of the road surface. The average uncertainty in an individual emission estimate for this measurement period was  $\pm 43$  g-PM<sub>10</sub>/VKT. Emission uncertainties were calculated by propagating the combined precision of the upwind and downwind mass concentration measurements through eq 1<sup>21</sup> (see Appendix 1). The variability between tests, as estimated by the standard deviation of emission factors, exceeds this measurement uncertainty.

Emission factors during the second intensive monitoring period, October 17–22 (see Table 2), show the untreated and BS test sections continued to have high and nearly equivalent emissions. The PEP test section showed a marked increase in its average emission factor ( $134 \pm 63$  g-PM<sub>10</sub>/VKT) over the factors measured in July. The PE test section continued to show good control efficiency. The average uncertainty for an individual emission factor for the October 1995 data was  $\pm 31$  g-PM<sub>10</sub>/VKT, still well below the standard deviation of the emission factors from the individual tests.

Emission factors for the final intensive monitoring period, June 13–18, 1996 (see Table 2), were lower for the untreated section ( $345 \pm 243$  g-PM<sub>10</sub>/VKT) than in previous tests, while the BS, PEP, and PE showed higher factors than before. The NHCO section had the lowest average emission rate of 24 ( $\pm 22$ ) g-PM<sub>10</sub>/VKT during this test, but it had experienced three months' less wear and tear than the others owing to its later application. The average uncertainty in an individual emission estimate was  $\pm 32$  g-PM<sub>10</sub>/VKT, still well below the variability between the tests.

In some cases the wind direction measured during a sampling interval approached a parallel flow to the road (see Table 1). An emission contribution from one test section to another downwind section is a possibility. However, measurements at additional locations downwind (15, 30, and 45 m) of the untreated section in June 1996, indicated that downwind concentration decreased as an exponential function. At 100 m downwind less than 0.01% of the initial concentration measured adjacent to the road would be detectable. The average distance between the sampling arrays was greater than 500 m, so contamination between sections was negligible.

The two samplers placed directly over the road were used to determine how much PM<sub>10</sub> could leave the road through vertical diffusion. Significant concentrations of PM<sub>10</sub> were observed in these samples for 54% of the test runs. The average percent contribution to the flux of PM<sub>10</sub> attributed to the overhead samplers was 4.1% ( $\pm 3.6\%$ ). Most of the PM<sub>10</sub> emitted from the unpaved road was moving horizontally with the dominant wind direction.

### Suppressant Control Efficiency

Suppressant efficiency is defined as the percent reduction

in emissions between the treated and untreated sections:

$$\text{efficiency} = 1 - \left( \frac{\text{treated emission factor}}{\text{untreated emission factor}} \right) \quad (3)$$

This calculation assumes that the environmental and use conditions, including weathering and traffic, and exposure history, were equivalent between the untreated and treated sections. This assumption is valid because measurements were taken simultaneously on each section for the same time periods on each day of testing and because the limited road length (3 km) tested did not extend into different meteorological or travel regimes.

Table 3 shows the efficiencies of the suppressants based on the PM<sub>10</sub> emission rates measured during the study period. Initially, the PEP and PE average efficiencies were 99% (±2%) and 94% (±6%), respectively. The BS treatment's average efficiency, 33% (±26%), was much lower.

With almost three months' weathering and vehicular traffic, the efficiencies of the BS and PEP decreased significantly from the first measurement period in July 1995. By October 1995, the BS section produced nearly the same PM<sub>10</sub> as the untreated section, as indicated by the -5% (±30%) efficiency. The PEP treatment reduced emissions by 72% (±8%), while the PE suppressant maintained the highest efficiency rating of 96% (±4%).

Eleven months after application, the PEP and PE efficiencies had declined further, while the BS section continued to produce PM<sub>10</sub> emissions at levels that were indistinguishable from the untreated section. The efficiency of the PEP suppressant declined to 49% (±10%), while the PE treatment's efficiency was reduced to 86% (±5%). After eight months' aging, the NHCO suppressant's efficiency was 92% (±6%), nearly the same as that of the PE efficiency after 11 months.

Figure 4 shows the change in average suppressant efficiency for the BS, PEP and PE treatments as a function of time from the date of application. Within the first year, there were substantial differences in the rate at which suppressant efficiency declined among the treatments. The PE suppressant efficiency decreased approximately seven times more slowly than the BS treatment and five times more slowly than the PEP. The data suggest that within the first year, the decline in suppressant efficiency can be described as a linear function of time.

### Surface Characterization Measurements

Changes in surface characteristics of the test sections resulted from exposure to weather and the continued action of vehicle traffic. Surface weathering was caused primarily by rainfall that probably caused aggregate breakdown or washout of some chemical-binding agents in the suppressants. In addition, solar radiation and heating

**Table 3.** PM<sub>10</sub> suppression efficiencies for each test during three intensive monitoring periods.

Date	Vehicle Speed (km/hr)	Suppressant Efficiency (%)			NHCO <sup>d</sup>
		BS <sup>a</sup>	PEP <sup>b</sup>	PE <sup>c</sup>	
7/22/95	40	56	100	100	N/A
7/24/95	40	20	100	83	
7/26/95	40	37	99	93	
(Average)		38	100	92	
(Std. Dev.)		18	1	8	
7/23/95	55	50	100	94	
7/25/95	55	47	99	100	
7/27/95 <sup>e</sup>	55	-13	94	97	
(Average)		28	98	97	
(Std. Dev.)		36	3	3	
10/17/95	40	3	73	97	N/A
10/20/95	40	-8	67	91	
10/22/95	40	-46	61	94	
(Average)		-17	67	94	
(Std. Dev.)		26	6	3	
10/18/95	55	-10	73	100	
10/21/95	55	37	84	100	
(Average)		13	79	100	
(Std. Dev.)		34	8	0	
6/13/96	40	18	65	90	83
6/14/96	40	-32	55	87	98
6/15/96	40	-20	42	86	89
(Average)		-11	54	88	90
(Std. Dev.)		26	11	2	7
6/16/96	55	-81	43	89	91
6/17/96	55	-75	37	77	97
6/18/96	55	-35	51	84	96
(Average)		-64	44	83	95
(Std. Dev.)		25	7	6	3

<sup>a</sup> Biocatalyst stabilizer (EMC<sup>2</sup>, Soil Stabilization Products).

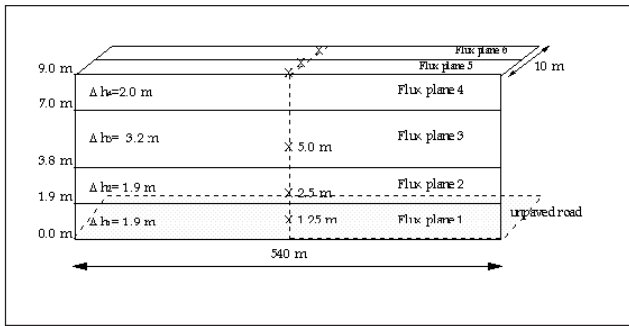
<sup>b</sup> Petroleum emulsion with polymer (CoherexPM, WITCO).

<sup>c</sup> Polymer emulsion (Soil Sement, Mid-West Ind. Supply).

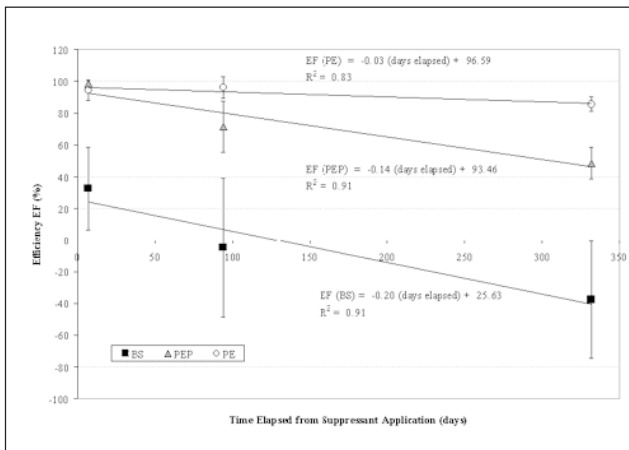
<sup>d</sup> Non-hazardous-crude-oil mixture (WSPA).

<sup>e</sup> Negative values denote emissions greater than the untreated section.

probably caused some weakening of suppressant adhesive properties and promoted evaporation of volatile components. Between August 1, 1995, and June 18, 1996, 344 mm of precipitation were recorded at the Merced County airport, approximately 48 km from Fields Road. During this period, rainfall was not recorded until December 1995, five months after the suppressants were applied. Above average rainfall amounts were observed in December 1995 and January, February, and May 1996.



**Figure 3.** The flux plane dimensions used in the emission calculation. The X marks the location of a MiniVol sampler and the concentration of PM<sub>10</sub> measured at each sampler location is assumed to represent the average concentration in a flux plane.



**Figure 4.** Changes in suppressant efficiency as a function of time elapsed since application.

Between July 1995 and August 1996, there were approximately 6,400 vehicle passes as determined by a traffic counter straddling two lanes. The NHCO section was subjected to approximately 4,900 vehicle passes before emission measurements were carried out in June 1996.

Figure 5a shows the changes in the bulk surface loading on the test sections as a function of time. Loose surface material loadings increased with time, except for a dip in December 1995. This was probably caused by higher moisture content from precipitation that incorporated material back into the road base and also washed away some of the looser material. This change is mirrored in the surface silt content (Figures 5b and 5c). Visual observations indicated that track-on of material between the sections was minimal and only visible within approximately 10 m either side of where two test sections joined. The surface loading measurements also indicate that there was minimal track-on of material between the adjacent test sections. If track-on had been significant it would have been most notable in the PE section, which was bounded by two sections (BS and PEP) that had much higher amounts of loose surface material. However, the PE section maintained relatively low amounts through the duration of

the study, indicating material was not being transported into the section.

Figure 5d shows changes in surface strength as a function of time. Surface strength generally increased with time on all the sections. The mean aggregate size data (see Figure 5e) show that mean diameter decreased for the PEP and PE sections and did not change for the BS, NHCO and untreated sections from July 1995 to August 1996.

The measured moisture contents at the time of the emissions measurements were less than 1% on average. Moisture contents less than 1% would not have significantly affected emissions between the different test surfaces. However, moisture content can have a significant effect on the surface properties as shown by the distinct changes observed in December 1995 (see Figure 5) when roadbed moisture content exceeded 4%.

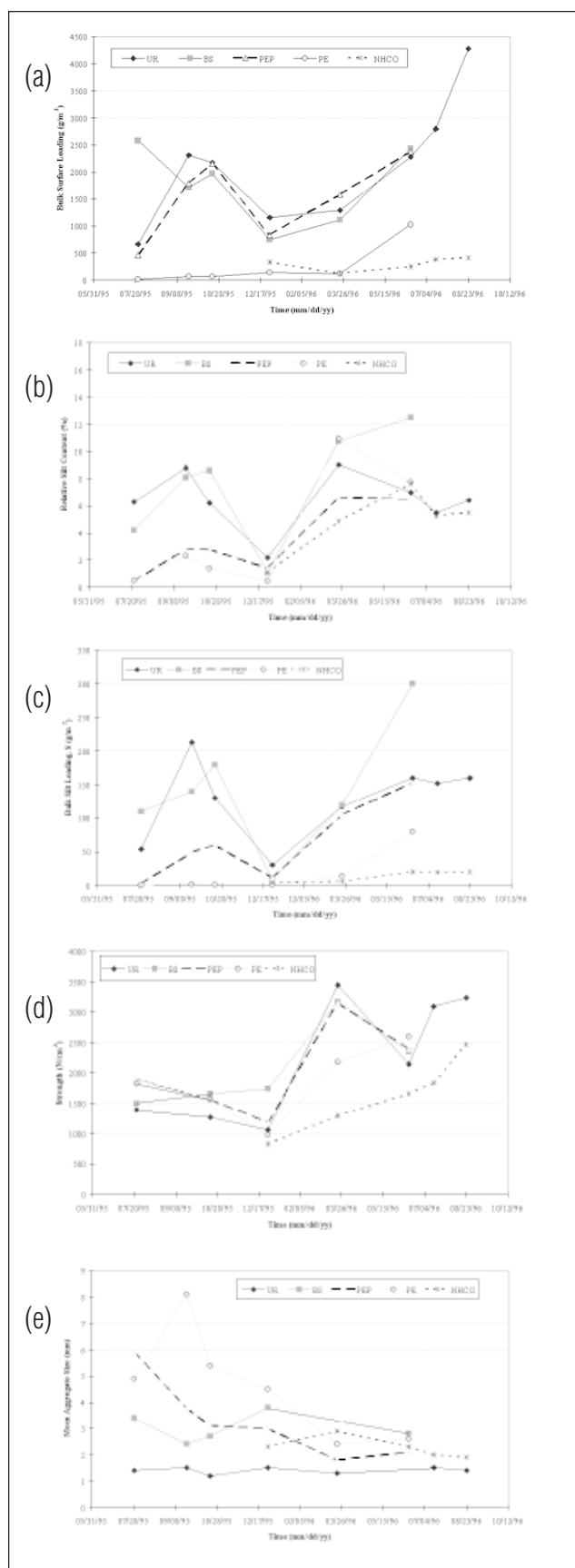
## DISCUSSION

### Emission Rates

The PM<sub>10</sub> emissions factors found in this study (see Table 2) are comparable to, and as variable as, those found in previous studies. On an untreated section of gravel road in Arizona, Stevens<sup>22</sup> measured factors ranging from 490 to 1,786 g-PM<sub>10</sub>/VKT for unpaved roads with silt contents between 4.3%–11% and typical vehicle speeds of 55–90 km/hr. The average emission factor from Stevens<sup>22</sup> untreated unpaved road with an average silt content of 7.5% was 950 (±491) g-PM<sub>10</sub>/VKT. By comparison, the average PM<sub>10</sub> emission factor for the untreated section of Fields Road (average silt content of 6.4%) was 523 (±357) g-PM<sub>10</sub>/VKT.

Flocchini et al.<sup>23</sup> measured PM<sub>10</sub> emissions on an unpaved and untreated agricultural road in the SJV and reported PM<sub>10</sub> emission factors ranging from 420–3,620 g-PM<sub>10</sub>/VKT for a 0.75-ton cargo van traveling at speeds between 16 km/hr and 40 km/hr. This range is larger than that found for the untreated section of Fields Road. There are significant differences between the two studies, however. The roadway Flocchini et al.<sup>23</sup> reported on had an average silt content of over 20%, approximately three times greater than the silt content of the untreated section of Fields Road. In addition, the silt loading (g/m<sup>2</sup>) of the Flocchini et al.<sup>23</sup> untreated test section was 1.6 times larger than on the untreated section of Fields Road. The vehicle speeds were significantly lower during the Flocchini et al.<sup>23</sup> tests, and the agricultural road was probably not as well-maintained and experienced more vehicular wear and tear from large farm vehicles than the county-maintained Fields Road.

For test sections that were treated with the suppressants lignin sulfonate, magnesium chloride, and an oil-based product, Flocchini et al.<sup>23</sup> reported PM<sub>10</sub> emission factors between 40 and 340 g-PM<sub>10</sub>/VKT. This is similar to the range of the average emission factors found in this study, 24–474 g-PM<sub>10</sub>/VKT for the suppressant-treated



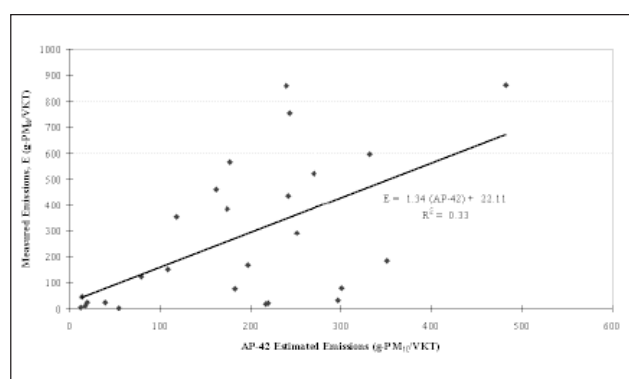
**Figure 5.** Changes in surface conditions as a function of time. (a) bulk loading, (b) relative silt content, (c) bulk silt loading, (d) surface strength, and (e) mean aggregate size.

test sections. The average suppressant efficiencies for the lignin sulfonate, magnesium chloride, and oil-based product were 99, 98, and 59%, respectively, for measurements taken one to five days after suppressant application. Effectiveness after longer periods were not quantified by Flocchini et al.<sup>23</sup>

Figure 6 compares emission factors for Fields Road test sections with U.S. EPA's AP-42 emission factors<sup>9</sup> using measured vehicle weights, silt contents and vehicle speeds for the Fields Road tests. Figure 6 shows considerable difference between the measured and AP-42 factors, similar to the Flocchini et al.<sup>23</sup> comparison. This study measured emission factors that were 1–3.5 times the values estimated by AP-42. Average AP-42 emission factors were 33% less than those of Table 2. Flocchini et al.<sup>23</sup> measured emission factors that were two to three times higher than AP-42 estimates with test-specific input values. Flocchini et al.<sup>23</sup> observed that the greatest divergence between AP-42 estimated values and measured values occurred when silt contents exceeded 20%.

The under-estimation by the AP-42 factor may be caused by its use of relative silt content as an input variable. A very small amount of surface material may consist mostly (to a high percentage) of silt, but this small reservoir would quickly be depleted. In this study, the emissions were not found to be dependent on the percent of silt in the material but on the silt mass loading. The bulk silt loading provides a better measure of the net amount of the source material available for resuspension and subsequent transport than the percent silt content used in AP-42.

Table 4 shows analysis of variance (ANOVA) for the emission factors determined within and between each intensive measurement period to determine the statistical significance of the observed differences. During the July tests no statistically significant difference in emission factors were found between the untreated and BS and between the PE and PEP sections. However, the emission rates of the high emitters (untreated and BS) differed significantly from the low emitters (PE and PEP).



**Figure 6.** Comparison of U.S. Environmental Protection Agency's AP-42 emissions factor and emission factors calculated for Fields Road.

During the October tests, the untreated and BS emissions were not statistically different. The PEP emissions differed significantly from all of the other emissions, as did the PE emissions.

By the June 1996 test, emissions from the untreated, BS and PEP sections did not differ significantly, even though Table 2 shows substantially lower emissions from the PEP surface. The PE and NHCO emission factors did not significantly differ from each other, but they were significantly different from the other treatments.

**Suppressant Efficiencies**

Differences in the suppressant control efficiencies examined with ANOVA follow a similar pattern to the emission factors (see Table 4). For the July 1995 test the BS efficiency in reducing PM<sub>10</sub> emissions was insignificant. The PE and PEP treatments were very efficient in reducing emissions, and the calculated efficiencies, 94% (±6%) and 99% (±2%), respectively, were not significantly different. In October 1995, the BS treatment was again ineffectual in reducing PM<sub>10</sub> emissions, and the PEP efficiency decreased significantly to 72% (±8%). The PE treatment maintained its high efficiency, 96% (±4%), in October 1995, with no significant reduction during the four months between emission measurements. For the final measurement period in June 1996, the BS treatment efficiency was not statistically different from the October 1995 values. The PEP efficiency decreased a further

23% by June 1996 compared to the October 1995 value. The PE efficiency significantly decreased to 86% (±5%). Since the emission rates for the PE and NHCO suppressants were not statistically significant in June 1996, their efficiencies also were not significantly different.

Figure 4 shows that the rates of decline in suppressant efficiency among the treatments were substantially different. For the duration of this study, the decline in suppressant efficiency appeared to follow a linear trend through time. However, for periods of time greater than one year, the efficiency would be expected to decrease at a much faster rate than a linear function. The data points shown in Figure 4 for the BS and PEP treatment suggest that the decay may be exponential, but the small number of data points precludes making any definitive judgment.

**Surface Characteristics and PM<sub>10</sub> Emissions**

The measured surface characteristics provide an indication of which properties effect the magnitude of the emissions and the effectiveness of the suppressants. No significant relationship was found in this study between the total bulk loading of surface material and PM<sub>10</sub> emissions. Previous studies<sup>9,23</sup> found percent silt content of the unpaved road surface was an important variable for dust emissions. The actual amount of silt present in the surface sediments, which potentially contains the reservoir of PM<sub>10</sub>, provides a more useful

**Table 4.** Analysis of variance for unpaved road emissions between suppressants and as function of time.

Suppressant	UN I1	UN I2	UN I3	BS I1	BS I2	BS I3	PEP I1	PEP I2	PEP I3	PE I1	PE I2	PE I3
UN <sup>a</sup> I1 <sup>b</sup>		I	I	I			S			S		
UN I2 <sup>c</sup>			I		I			S			S	
UN I3 <sup>d</sup>						I			I			S
BS <sup>e</sup> I1					I	I	S	S	S	S	S	S
BS I2						I		S	S		S	S
BS I3									I			S
PEP <sup>f</sup> I1								S	S	I	S	S
PEP I2									I		S	S
PEP I3												S
PE <sup>g</sup> I1											I	I
PE I2												I
PE I3												
NHCO <sup>h</sup> I3			S			S			S			I

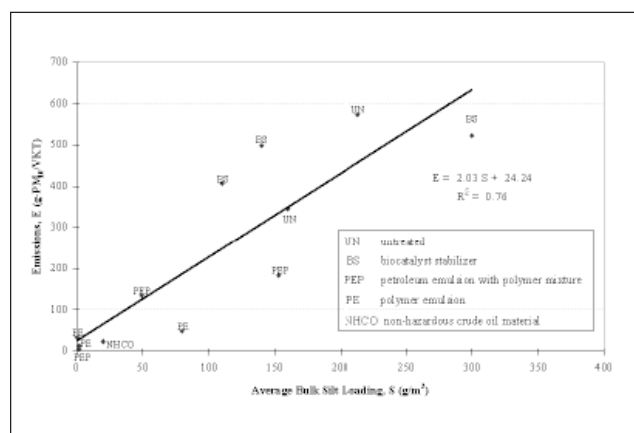
I = No statistical significance; S = Significant statistical difference.

<sup>a</sup>Untreated; <sup>b</sup>July 1995; <sup>c</sup>October 1995; <sup>d</sup>June 1996; <sup>e</sup>Biocatalyst stabilizer (EMC<sup>2</sup>, Soil Stabilization Products); <sup>f</sup>Petroleum emulsion and polymer mixture (Coherex PM, Reed-Graham); <sup>g</sup>Polymer emulsion (Soil Sement, Mid-West Ind. Supply); <sup>h</sup>Non-hazardous-crude-oil Mixture (WSPA).

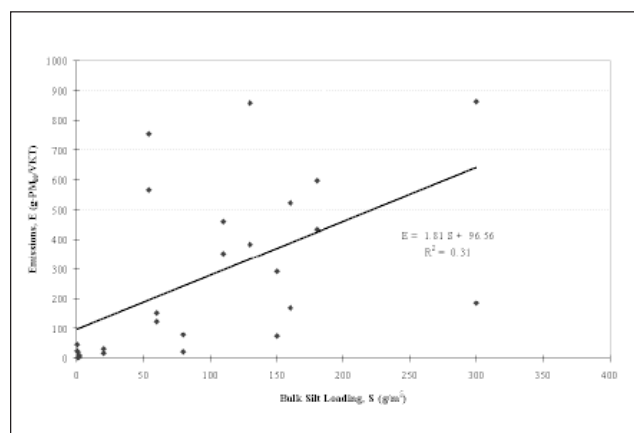
measure of emission potential than the total amount of loose surface material or its relative silt content. The relationship between the average bulk surface loading of silt particles and the average emission rates is shown in Figure 7.

Figure 8 shows this relationship using the individual test emissions data and not the averaged emission factors. There is considerable scatter in the relationship, but this scatter is reduced when vehicle speed is taken into account, particularly for the higher speed tests (see Figure 9). Higher vehicle speeds are more effective in injecting  $PM_{10}$  from the reservoir into ambient air. The process is complicated further because  $PM_{10}$  emissions are not only a function of existing  $PM_{10}$  particles injected into the air stream by the vehicles. Additional particles in the  $PM_{10}$  size range are produced by the action of the vehicle tires on the road surface; vehicles traveling at higher speeds may produce more particles.

The importance of total surface silt loading becomes more evident through an examination of the loading and suppressant efficiency data. The lowest  $PM_{10}$  emission rates were recorded for the PE, PEP, and NHCO surfaces, which



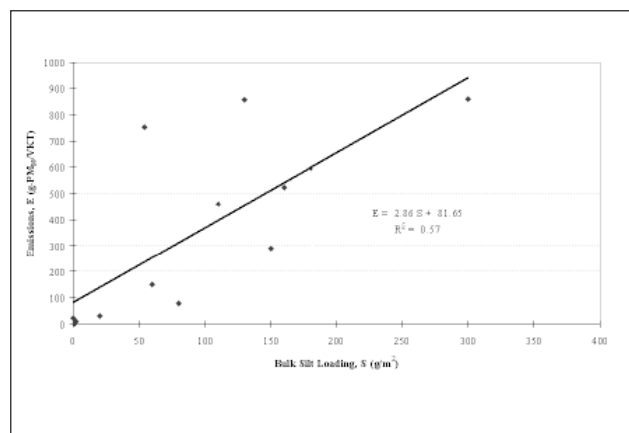
**Figure 7.** Average emission rate as a function of average bulk surface loading of silt.



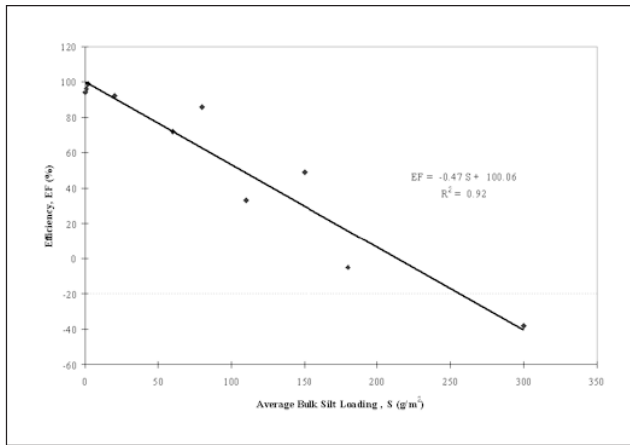
**Figure 8.** Emission factors and bulk surface loading of silt for individual test runs.

also had the lowest measured bulk surface loading of silt for the duration of this study. In July 1995, the average silt loading for PE and PEP (see Figure 5c) were, respectively, 0.1 and 2  $g/m^2$ . These values are several orders of magnitude lower than those of the untreated (54  $g/m^2$ ) and BS (110  $g/m^2$ ) sections that produced relatively high amounts of  $PM_{10}$ . In October 1995, the low-emitting, high-efficiency PE suppressant maintained a low silt loading of 2  $g/m^2$ . The increase in silt content through time is clearly correlated with increasing  $PM_{10}$  emission factors and decreasing suppressant efficiency. The relationship between average silt loading and  $PM_{10}$  reduction efficiency is shown in Figure 10. Figure 10 shows that 50% efficiency is achieved by maintaining bulk surface loading of silt below  $\sim 100$   $g/m^2$  and 99% efficiency is achieved at a loading below  $\sim 2$   $g/m^2$ .

The low silt loading of the efficient suppressants is a function of the conditions they create when applied to the unpaved road surface and their ability to withstand the degradation processes of weathering and vehicle traffic. The surface strength measurements provide some insight about the long-term efficiency of the PE and NHCO suppressants. Two distinctly different responses to the applied vertical force of the penetrometer were observed on different test sections. For the PE and NHCO sections, the penetrometer entered the surface with a slower, deforming-type penetration. While this created a small hole in the surface, it did not shatter the surrounding surface. Penetration on the other three sections is best described as a brittle failure. In this case the surface responded to the applied pressure at some point by “shattering” and creating small aggregates. The deformation-type penetration was observed on all sections in December 1995, when the moisture content of the sediment exceeded 4% by weight. The strength measurements do not differentiate the two failure types and, in some cases, may show equivalence between sections; however the mode of failure has important implications for emissions reduction.



**Figure 9.** Emission factors and bulk surface loading of silt for individual test runs with vehicle speed equal to 55 km/hr.



**Figure 10.** The relationship between the average silt loading of the loose surface material and the percent efficiency of  $PM_{10}$  emissions reduction.

In brittle failure, particles are created that can subsequently be ground up by tires providing a source material for emissions. In plastic deformation, no particles are created upon failure and the roadbed can deform under an applied vertical stress without rupturing. The PE and NHCO use two different physical mechanisms to create these plastic failure conditions, but the result is the same—increased effectiveness of  $PM_{10}$  emissions reduction. The PE suppressant creates a pliable surface film, while the NHCO uses a binding agent that cures slowly through time and maintains a degree of flexibility in the sediment matrix. How often a surface, such as the PE or NHCO section, can plastically deform before it is subject to brittle failure is not yet known.

An additional important aspect with respect to the PE suppressant efficiency is the protective surface film it forms that effectively seals the underlying road material beneath it. The film is resistant to the wear and tear of tires, except when the tires are turned sharply, which creates a high shearing force that tears the surface film open, exposing the sediments underneath. The PE film resists tearing due to its strength characteristics and ability to deform plastically under regular public unpaved road traffic conditions when shear stresses are lower. The increased emission rates on the PE section during the final emissions testing can be attributed to the sporadic breakdown of the protective film and the exposure of the underlying sediment, which became available for injection by the test vehicle. In June 1996, the surface film was judged to be approximately 35% disturbed in a random pattern, which still provided an efficiency for  $PM_{10}$  reduction of 86%.

This study has demonstrated that some simple methods, based on measuring surface characteristics, can be used to estimate suppressant effectiveness in place of expensive emission monitoring for evaluating treatment efficiencies. Measurement of the bulk silt loading and the surface strength can provide an effective method to rap-

idly and inexpensively assess a suppressant's effectiveness to reduce  $PM_{10}$  emissions. If a surface treated with a dust suppressant can achieve bulk surface silt contents of less than  $20 \text{ g/m}^2$ , then it is highly effective in reducing  $PM_{10}$  emissions (>90% effective). In addition, if the suppressant can maintain flexibility of the road surface, as indicated by penetrometer measurements and the associated form of surface failure, the production of fine material will be reduced, increasing its longevity. These two surface properties could be used to screen untested newly developed products that, upon receiving a good rating, could be tested using the upwind/downwind measurement technique to verify their effectiveness.

Several limitations of this study should be addressed with continued research. The methodological approach that was applied limited the number of vehicle speeds tested, and the emissions were measured from only one road type: a public unpaved road. The measured emission factors and suppressant effectiveness may be quite different on roadways used by heavier vehicles such as construction site and mining roads where material dropped from vehicles is constantly added to the road surface. This added material eventually could cover the suppressed surfaces with loose material, rendering the suppressant ineffective in a short period of time. Agricultural roads often are used for only a few weeks during field preparation and harvest. Very heavy vehicles with tire treads or tracks travel these roads, and the successful suppressants might not withstand this type of use.

### Regionwide $PM_{10}$ Emissions Reduction Potential in the San Joaquin Valley

$PM_{10}$  emissions from public unpaved roads are not distinguished from other unpaved road (e.g., agricultural, construction, mining) emissions of  $1 \times 10^5 \text{ kg/day}$  in the eight SJV counties. If one assumes  $\sim 5,000 \text{ km}$  of public unpaved roads in the SJV, an average of 5,000 vehicle passes per year at  $\sim 40 \text{ km/hour}$ ,  $\sim 600 \text{ g-PM}_{10}/\text{VKT}$  as an emission factor, and untreated silt loadings similar to that of Fields Road,  $\sim 4.2 \times 10^4 \text{ kg/day}$ , or approximately 40%, of the unpaved road total  $PM_{10}$  in the inventory can be accounted for.

The costs of applying the best of the tested suppressants, Soil Sement, for this study were  $\$.69 \text{ per m}^2$  or approximately  $\$6,900 \text{ per km}$  of unpaved road, assuming a road width of 10 m. Assuming an annual average  $PM_{10}$  reduction of 90%, with suppressant applied every year, the total SJV  $PM_{10}$  fugitive dust emissions estimate of  $3.4 \times 10^5 \text{ kg/day}$  would be reduced by  $\sim 11\%$  to  $3.02 \times 10^5 \text{ kg/day}$  at an annual cost of  $\sim \$34,500,000$ . This is only an order of magnitude estimate of overall efficiency that needs to be refined later for the consideration of where and when  $PM_{10}$  standards are exceeded and which roads and other sources are contributing to those exceedances.

## CONCLUSIONS

Emission rates were measured during three intensive study periods in July 1995, October 1995, and June 1996 for unpaved roadway sections treated with four chemical suppressants and an untreated section. Emission factors estimated from the untreated and suppressant-treated unpaved road sections ranged from zero to 800 g-PM<sub>10</sub>/VKT at a vehicle speed of 40 km/hr and from zero to 1,361 g-PM<sub>10</sub>/VKT at a vehicle speed of 55 km/hr.

Unpaved road PM<sub>10</sub> emission rates from this study are similar to, but as variable as, those found in other studies.<sup>22,23</sup> The U.S. EPA AP-42 emission factor underestimated Fields Road emission by up to 71% but, on average, by only 23% when it was applied to traffic and silt contents measured on Fields Road.

The measured efficiencies of the suppressant products varied widely. The PE (Soil Sement) established a durable and flexible surface coating on the unpaved road. It was an effective suppressant, even after 6,400 vehicle passes and 12 months of weathering, including the effects of an unusually wet winter. The efficiency of this product exceeded 80%, on average, during the final measurement period, 12 months after application. The NHCO was 95% efficient after eight months' aging. The efficiency of the PEP mixture (Coherex PM) was 73% after three months and 49% after 12 months. This product was effective during the first intensive study period and did survive winter weather, but deteriorated significantly during the study. The BS product (EMC<sup>2</sup>) was only marginally efficient (33%) during the first intensive measurement period; it deteriorated rapidly even before winter weather occurred.

The major surface properties that define low-emitting, well-suppressed surfaces are (1) surface silt loading and (2) the strength and flexibility of suppressant material as a surface layer or cover. Silt loading is the best indicator of suppressant efficiency. Silt loadings of less than 22 g/m<sup>2</sup> are associated with efficiencies that exceed 90%. Silt loadings that exceed 200 g/m<sup>2</sup> are no different from untreated sections in terms of efficiency. Suppressants that create surface conditions that allow plastic deformation or resist brittle failure have an increased likelihood for long-term reduction efficiency for PM<sub>10</sub> emissions on unpaved roads.

## ACKNOWLEDGMENTS

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## DISCLAIMER

This study does not necessarily reflect the policies or views of the California Regional Particulate Air Quality Study, the San Joaquin Valley Unified Air Pollution Control District, or the Western States Petroleum Association. The mention of trade names and commercial products does not constitute endorsement for those products.

## APPENDIX 1

A sample emission factor calculation and its associated uncertainty is given below using typical ambient PM<sub>10</sub> and environmental data, average vehicle kilometers traveled, sampling duration of six hours, and the actual flux plane dimensions.

- (1) Upwind PM<sub>10</sub> concentration = 25 (±8) µg/m<sup>3</sup>.
- (2) Downwind PM<sub>10</sub> concentrations: 300 (±18) µg/m<sup>3</sup> at 1.25 m above ground level (AGL), 150 (±10) µg/m<sup>3</sup> at 2.5 m AGL, 80 (±9) µg/m<sup>3</sup> at 5 m AGL, 40 (±8) µg/m<sup>3</sup> at 9 m AGL, 30 (±8) µg/m<sup>3</sup> at 9 m AGL and 3 m from tower (over the road), 30 (±8) µg/m<sup>3</sup> at 9 m AGL and 6 m from tower (over the road).
- (3) Environmental conditions: wind speeds 2.4 m/sec at 1.25 m, 2.6 m/sec at 2.5 m, 2.8 m/sec at 5 m, and 3 m/sec at 9 m. Wind friction speed:  $u_*$ , 0.14 m/sec. Wind direction: 350°.
- (4) Example calculation for flux plane 1 emission rate (eq 1): 300 µg/m<sup>3</sup> is a real measure of roadway emissions because  $(300 \mu\text{g}/\text{m}^3 - 25 \mu\text{g}/\text{m}^3) > (18^2 + 8^2)^{0.5}$  (the RMS value of the two associated uncertainties). Therefore, the emission rate in flux plane 1 is:  $[(300 \mu\text{g}/\text{m}^3 - 25 \mu\text{g}/\text{m}^3) \times 2.4 \text{ m}/\text{sec} \times \cos 350^\circ \times 1.9 \text{ m} \times 541 \text{ m}] = 6.6 \times 10^5 \mu\text{g}/\text{sec}$ .  
The sum for all six flux planes is  $1.3 \times 10^6 \mu\text{g}/\text{sec}$ .
- (5) Emission factor calculation:  
$$\frac{1.3 \times 10^6 \mu\text{g}/\text{s}}{60\text{km}} \times 3600\text{s} \times 6\text{hrs} \times 10^{-6} \text{g} = 470 \text{g} - \text{PM}_{10} / \text{VKT}$$
- (6) Associated uncertainty estimate (only flux plane 1 calculation is shown in detail). The RMS error of the combined upwind and downwind measurements is 19.7 µg/m<sup>3</sup>. This RMS value is used to calculate the emission rate uncertainty in the flux plane:  $[(19.7 \mu\text{g}/\text{m}^3) \times 2.4 \text{ m}/\text{sec} \times \cos 350^\circ \times 1.9 \text{ m} \times 541 \text{ m}] = 4.8 \times 10^4 \mu\text{g}/\text{sec}$ .  
The sum for all six flux planes is  $1.8 \times 10^5 \mu\text{g}/\text{sec}$ .
- (7) Emission uncertainty calculation:  
$$\frac{1.8 \times 10^5 \mu\text{g}/\text{sec}}{60\text{km}} \times 3600\text{sec} \times 6\text{hrs} \times 10^{-6} \text{g} = \pm 66 \text{g} - \text{PM}_{10} / \text{VKT}$$

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