Predicting Dust Palliative Effectiveness on Unpaved Roads Using a Simple Laboratory Procedure

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Abstract

The ability of palliatives such as hygroscopic salts and synthetic fluids to reduce dust emissions from unpaved roads and other unpaved surfaces is well known. However, the effectiveness of different products used to control the loss of fine aggregate particles has largely been evaluated by observing the intensity of dust plumes produced behind moving vehicles. Currently, no standardized laboratory test exists for predicting dust palliative performance. Presented here is a laboratory methodology capable of predicting the effectiveness of palliatives applied to unpaved aggregate surfaces. The procedure evaluates the ability of palliatives to retain fine particles by measuring the total mass of PM_{10} (particulate matter less than 10 µm in size) present in material abraded from the treated aggregate surface. Total mass is determined by measuring PM_{10} concentrations in settling dust resulting from propelling a sample into a column. The test methodology is simple yet provides repeatable results. Moreover, the resolution in the test results is high enough to distinguish the performance between different palliatives applied at different application rates. Minor limitations are inherent in the methodology owing to the natural heterogeneity that exists in compacted aggregates. These limitations can be reduced with careful sample preparation.

Introduction

Over 1.3 million miles of unpaved roads in the United States contribute about 5.8 million tons of PM_{10} (particulate matter less than 10 micron in size) to the atmosphere yearly, accounting for 42% of total PM_{10} emissions from stationary sources (U.S. Department of Transportation, 2025; U.S. Environmental Protection Agency, 2025). Effective road dust palliatives like calcium chloride and synthetic fluids can control these emissions. However, there is no universal laboratory method to determine the optimal amount of palliative to apply or effectiveness of palliatives. This study developed a standard laboratory test to assess their effectiveness. The proposed test is simple, produces consistent results, and distinguishes performance among palliatives and applications.

Farm-to-market roads, forest service roads, and community roads are all examples of unpaved roadways. Anyone who has driven on an unpaved road has observed the clouds of road dust generated as the vehicle travels down the path. These clouds of particulate matter signify a material loss from the road, leading to a degradation of road integrity. In addition, road dust poses respiratory health risks, safety concerns, and diminished quality of life for people living near unpaved roads.

The management of road dust has been addressed in road design literature since at least the 1890s, albeit for a much different transportation system than today (Love, 1890). Early methods focused on road watering, the use of hygroscopic salts, asphaltic oils, and petroleum residuals, several of which remain prevalent in current practices (Agg, 1916; Baker, 1918; Barnes and Connor, 2014). In the mid-20th century, the application of waste oils to road surfaces became common, resulting in the well-known disaster in Times Beach, Missouri, where waste oils containing dioxane were used (Hites, 2011). Modern road dust management involves the application of products such as emulsions, synthetic fluids,

lignosulphonates, and calcium and magnesium chloride to maintain road integrity and manage dust emissions.

The effectiveness of dust palliatives on gravel roads after application is primarily influenced by the gradation of the surface course material, the physical and chemical properties of the applied palliative, and the amount per road area applied (Barnes and Connor, 2014). Additionally, factors such as road design, average daily traffic, and vehicle type and speed affect the duration of dust palliative applications. With over 200 named products being marketed in North America for dust control or soil stabilization, road managers require a standardized testing method to determine the product's effectiveness and the optimal application rate prior to deployment.

Several field-testing methods have been developed to assess the efficacy of dust palliatives post-application (Sanders and Addo, 2000; Kuhns et al., 2001; Etyemezian et al., 2003; Thenoux et al., 2007; Eckhoff, 2012). These methods involve vehicle-mounted mobile monitors that measure dust production behind moving vehicles. While useful, these methods are time-consuming and expensive, as they require the application of palliatives over several hundred-meter test sections, followed by performance monitoring over extended periods.

The predictive palliative performance test presented here is a laboratory-based method, suitable for evaluating multiple palliatives at varying application rates. This proposed test aims to provide road managers with a practical and efficient tool for predicting the effectiveness of dust control treatments before field application, leading to more informed decision-making and optimized resource allocation.

Method Description

The primary objective of the test methodology is to evaluate the ability of a dust palliative to retain road aggregate particles 10 micron and smaller (PM_{10}) in the top few millimeters of the compacted aggregate surface. This evaluation is accomplished by physically abrading material off the top of a compacted and palliative treated aggregate surface and measuring the total mass of PM_{10} particles contained in the loosened material. Total PM_{10} mass is measured by lofting samples of the abraded material into a column with a puff of air and measuring PM_{10} concentrations in the dust fall by nephelometry. The test method is a refinement of a procedure developed by the authors and subsequently adopted by the Alaska Department of Transportation and Public Facilities (ADOT&PF) as Alaska Test Method (ATM) 316 (Alaska Department of Transportation and Public Facilities, 2020).

During the development of this testing methodology, efforts were made to ensure the use of equipment commonly available in standard materials testing laboratories or readily procurable from commercial suppliers. Certain specialized apparatus required for the procedure, however, necessitated custom fabrication. The method is designed to be applicable to aggregate samples that are laboratory prepared and aggregate samples that are obtained directly from field sampling. These tests are known as laboratory-abraded tests. The test can also be performed on soil samples that are obtained directly from palliative-treated surfaces (field-abraded tests). Detailed descriptions of each component of the method are provided in the subsequent sections. A revised version of Alaska Test Method 316 (ATM 316), delineating the specific procedural steps, is included in the supplementary materials.

Sample Preparation

Aggregate samples that are prepared in the laboratory or field obtained samples (laboratory-abraded samples) require preparation before measuring the total PM_{10} mass. This preparation involves determining the optimum moisture content, removing aggregate particles larger than 4.75 mm retained on a #4 sieve, and compacting the sample in 15.24 cm (6 in) diameter California Bearing Ratio (CBR) molds. A specified volume of the palliative to be tested is uniformly applied to the top of the compacted aggregate and allowed to maturate for 14 days. The application rate (typically expressed as a ratio of unit area to volume applied) of the palliative is predetermined based on the planned field application for road surfaces. Alternatively, the palliative may be integrated into the uppermost few centimeters of the aggregate layer and then compacted into the mold. This application method simulates the application methodology commonly used for calcium or magnesium chloride-based dust palliatives on unpaved road surfaces. Multiple molds are prepared to test the palliative for replicate testing, typically three molds, referred to as a mold replicate.

Abrasion

The abrasion process simulates the dislodging of particles caused by vehicle tires during motion, particularly during acceleration, braking, or when navigating curves. However, it is important to note that it is not intended for the method of abrasion used in this test to replicate the comprehensive physical impact of vehicle traffic on an unpaved surface.

After the designated maturation period, the compacted aggregate surface within the CBR mold undergoes abrasion utilizing a custom-fabricated apparatus referred to as an abrader (shown in Figure 1). This device is equipped with an 80-grit sanding disc affixed to its base and weighted with a standard load of 4.54 kg (10 lbs) at the top. The abrader is systematically rotated atop the aggregate surface, enclosed by a CBR collar, for a predetermined number of rotations. The resulting abraded material is collected and stored in an airtight soil container for subsequent analysis. The mass of abraded material collected should be great enough to support at least five tests in the column to determine PM_{10} concentrations. Each test of a sampling of the abraded material in the column is known as a sample run.

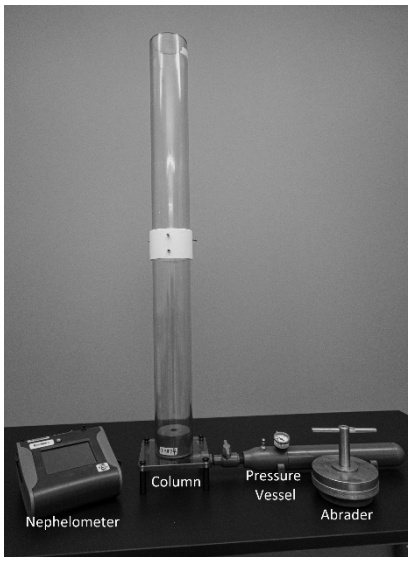

Figure. 1. *Column aparatus and abrader*

PM_{10} Concentration Measurement

To measure PM_{10} concentrations in the abraded material, samples are lofted into the column measuring 1.09 m tall by 0.10 m outside diameter. The column sits on a 17.5 cm by 17.5 cm base containing a 1.8 cm diameter sample well. The bottom of the sample well is screened to hold the sample and directly connected to a valved pressure vessel. When the valve is opened the pressurized air propels the sample into the column. PM_{10} concentrations are measured in the column as the sample particles settle. Figure 1 shows the column apparatus.

This methodology uses a commercially available nephelometer to measure PM_{10} concentrations (Figure 1). The nephelometer is connected to the column through a port and measures the PM_{10} concentrations in a 1.0 L/min air flow pulled from the column at one second intervals. At the beginning of the sample run, two grams of the homogenized collected soil are placed into the column's sample well. The background PM_{10} concentration in the column is measured by the nephelometer prior to lofting the sample into the column. Background concentration measurements are taken for at least thirty seconds. Thirty seconds is chosen to provide sufficient time to clear any remaining particulate material from the tubing connecting the nephelometer to the column and from the internal chambers in the nephelometer as well as provide enough measurements to determine the average background concentration.

Following the background concentration measurement, a lid is placed on top of the column and compressed air is released to propel the material upward within the column. As the particles settle, the concentration of PM_{10} within the air column is recorded at one-second intervals by the nephelometer. Concentration measurements are continuously recorded until the PM_{10} concentration in the column reaches an estimated background concentration, which is estimated from concentration readings displayed on the nephelometer prior to lofting the sample. The volume of compressed air used to propel the sample is standardized to 0.602 L at a pressure of 137.89 kPa (20 psi). These parameters were validated to ensure precision and repeatability.

Following completion of the sample run the background PM_{10} concentration is determined by averaging the fifteen concentration measurements recorded prior to propelling the sample into the column. The background PM_{10} concentration is subtracted from the PM_{10} concentrations measured in the column during particle settling resulting in the final PM_{10} concentrations for the sample run (Equation 1).

$$\acute{C}_i = C_i - C_b \qquad (1)$$

In Equation (1), $\acute{C}_i$ equals the concentration of PM_{10} in the column at timestep i minus the measured background concentration, C_i equals the concentration measured in the column during particle settling at time step i, and C_b equals the average background concentration in the column prior to propelling the sample. The total mass of PM_{10} in the puffed sample (M_{tot}^{s}) is calculated from these final PM_{10} concentration values. Five or more sample runs are conducted on the abraded material obtained from each replicate mold. Typical $\acute{C}$ results for a sample run are shown in Figure 2.

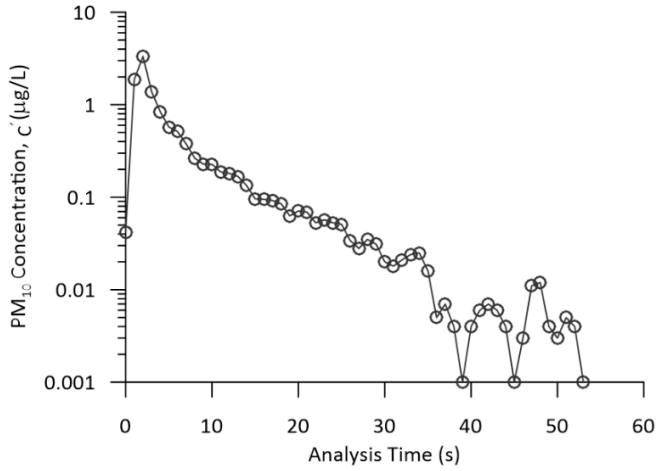

Figure. 2. *Typical PM_{10} concentration results for a sample run of abraded material.*

Results Analysis

Referring to Figure 2, calculation of M_{tot}^{s} is a numerical integration of the resulting concentration with time curve generated for each replicate following the trapezoidal rule (Equation 2).

$$M_{tot}^{s} = \sum_{i=1}^{i=n} \left(\frac{\acute{C}_{i-1} + \acute{C}_{i}}{2} \right) \cdot Q_{air} \cdot \Delta t \qquad (2)$$

In Equation (2), Q_{air} is the flow rate of the air pulled through the nephelometer (1.0 L/min), Δt equals sampling interval (1.0 s), and n equals the number of time steps recorded prior to reaching the first measured background concentration, C_b.

The total PM_{10} mass in the sample serves as an indicator of the effectiveness of a palliative in mitigating PM_{10} emissions from treated unpaved surfaces. A small value of M_{tot}^{s} suggests adequate particle retention within the surface layer, reducing particulate emissions caused by vehicular activity. This retention is attributed to the binding properties of the palliative, as described by Barnes and Connor (2014).

However, the effectiveness of a palliative cannot solely be assessed by a low M_{tot}^{s} value. Samples with predominantly small particles will inherently exhibit lower total particulate mass compared to those containing larger particles. Therefore, an evaluation of particle size distribution is essential, which can be inferred from the principle of Stokes' Law. Settling rates of particulates in air are size-dependent, with larger particles settling more rapidly. A well-performing palliative would exhibit both a low M_{tot}^{s} and a short settling time for a significant fraction of the total mass.

Experimental results comparing two palliatives, designated Product A and Product B, illustrate this principle. Figure 3 shows these results. While the M_{tot}^{s} values measured in the test of Product A (0.57 µg) and the test of Product B (0.58 µg) are nearly identical, the settling times to reach background concentration (0.002 µg/L for test of Product A and 0.003 µg/L for test of Product B) exhibit significant variation. Product B required 172 seconds, whereas Product A required only 54 seconds. This disparity indicates that Product B's sample contains a higher proportion of smaller particles, suggesting reduced retention of fine aggregate within the surface layer. Consequently, even though tests of both products

resulted in nearly equivalent values of M_{tot}^{s}, Product A demonstrates comparatively better performance in retaining particulate matter over the range of large (10 µm) to very small sized particles.

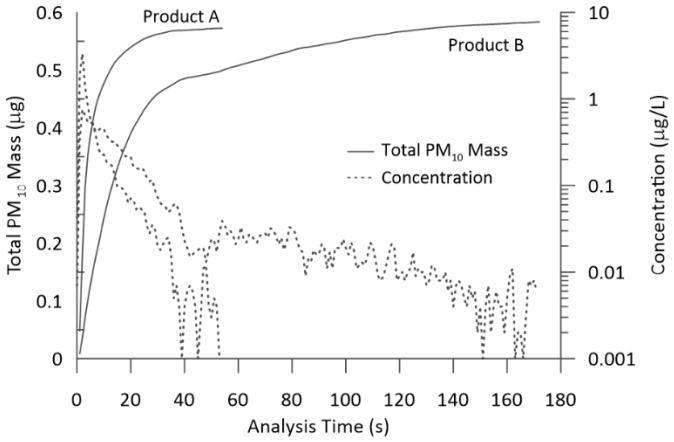

Figure. 3. *Comparison of two products with nearly identical total PM_{10}.*

For this methodology the time for 90% of M_{tot}^{s} to settle was selected as the measure for how well a palliative is retaining the smallest particles in the surface layer. This variable is known as t90. The use of t90 was chosen over the more direct measurement of the time required to reach background concentrations (t_n) in the column due to the wide variability of t_n between test replicates of the same abraded material. The measured t90 for a sample run includes superscript s in the variable name, $t90^s$. Well performing palliatives will have low mean values of both M_{tot}^{s} and $t90^s$ measured over several sample runs. Figure 4 shows the relationship between mean values of mean M_{tot}^{s} and $t90^s$ relative to how a palliative is performing.

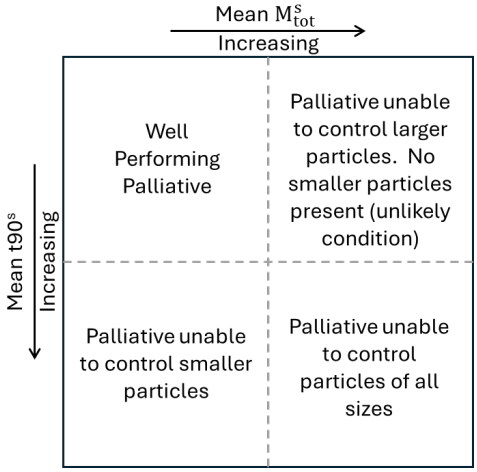

Figure. 4. *Relationship between mean total mass and mean time to reach 90% total mass.*

Results of M_{tot}^{s} across multiple mold replicates for a particular product and application rate are analyzed using a one-way analysis of variance (ANOVA) to assess whether significant differences exist among the mean M_{tot}^{s} values obtained for each mold ($\overline{M}_{tot}^{m}$). If the analysis indicates no statistically significant differences between $\overline{M}_{tot}^{m}$ values measured for each mold replicate, M_{tot}^{s} values determined from each sample run from the replicate molds are grouped into one dataset for subsequent statistical

characterization. However, if results from ANOVA testing indicate that the means are significantly different, a two-sample t-test (single tail and equal variance) is used to determine which specific replicate mold $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values are significantly different. Following this analysis, if all $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values from the replicate molds are significantly different, then the entire test is re-run starting with mold compaction. Otherwise, the sample run $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ values measured from the replicate molds with statistically similar $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ are grouped for statistical characterization. Statistical comparisons of palliative performance between products and application rates are made using the grouped data sets. Specifically, the mean value of $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$for the grouped data set, known as the mean total mass of the application ($\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$) and the standard deviation in $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ for the application, $\mathrm{std}(\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}})$, are used for the comparison.

Experience with this test methodology has shown that variations in $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values among mold replicate treated with the same product at identical application rate may stem from differences in the aggregate surface condition within each mold. Observations have shown that the $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ values measured from a mold with a treated aggregate exhibiting a more porous surface texture yield $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values distinct from those with surfaces characterized by smaller pore openings. These differences in the aggregate surface condition develop during mold compaction and are inherently difficult to control. However, it is worth noting that variations in field compaction of surface aggregates on unpaved roads will also be inconsistent, hence the performance of any palliative will vary spatially on any unpaved road.

Adaption of the Method for Field Testing

This methodology can also be applied to evaluate the effectiveness of palliatives on unpaved surfaces by analyzing field-abrasion samples retrieved directly from the treated area. The abrasion process employs the same abrader device shown in Figure 1, with the applied weight increased to 6.80 kg (15 lbs) from the 4.54 kg (10 lbs) utilized in laboratory-based abrasion procedures. Abraded material is collected from the unpaved surface using a soft-bristled brush and stored in an airtight soil container to preserve the sample integrity until it can be tested. Given the portability of the column setup, on-site measurements of $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ and $t90^{s}$ can be conducted, provided electrical power and a precision balance is available for accurately weighing the sample mass for testing. All other aspects of the methodology remain consistent with the laboratory procedure.

Test Method Evaluation

Four different proprietary palliatives were evaluated using this methodology: two synthetic fluid type palliatives (SF1 and SF2) and two emulsion type palliatives (E1 and E2). Calcium chloride ($CaCl_2$) was evaluated as well. All palliatives except $CaCl_2$ were evaluated at different application rates as shown in Table 1. Palliative applications were cured two weeks prior to abrasion.

Table 1. Palliative product application rates evaluated

Palliative	Application Amounts
SF1 and SF2	0.74 m^2/L (30 ft^2/gal), 0.98 m^2/L (40 ft^2/gal), 1.23 m^2/L, (50 ft^2/gal), 1.47 m^2/L (60 ft^2/gal)
E1	0.74 m^2/L (30 ft^2/gal), 0.98 m^2/L (40 ft^2/gal), 1.47 m^2/L (60 ft^2/gal)
E2	1:1 (1-part water to 1-part product), 1.5:1, 2:1, 4:1
$CaCl_2$	35% brine solution applied at 0.86 L/m^2, cured in 50% humidity chamber

Palliatives SF1, SF2, and E1 were applied to a laboratory prepared aggregate. Palliatives E2 and $CaCl_2$ were applied to a field obtained aggregate. Table 2 provides the particle distribution for these aggregates with the plus #4 aggregate removed.

Table 2. Particle distributions for aggregates used in product evaluations

		Percent Passing (%)	
Size (mm)	Sieve #	Laboratory Prepared	Field Obtained
9.5	4	100	100
2.36	8	70	73
0.30	50	45	41
0.75	200	23	10

Results and Discussion

Effective dust management on unpaved roads requires the ability to predict performance of different palliatives prior to application and the proper application rate. High application rates may not be needed to sufficiently retain particles in the aggregate surface, hence may not be a wise choice economically. Too little applied palliative will result in insufficient retention of particles in the aggregate surface and the application will have a short effective lifespan. The ability of this methodology to predict how well a palliative will retain PM_{10} sized particles once applied to an unpaved road will be shown by comparing the performance of different palliatives applied to aggregate surfaces at equal application rates as well as to discern performance of palliatives applied at different application rates. Testing results from the five different products will be used in the discussion of the methodology. Table 3 provides the statistical characterization of these results. The statistical characterization of grouped data sets that represent the characteristics of the product application are noted in the table.

Table 3. Statistical characterization for products evaluated

				M_{tot}^{s}				T90^{s}			
Results Number	Product	Application Rate	Replicates	Mean (µg)	std (µg)	CV	95% CI (µg)	Mean (s)	std (s)	CV	95% CI (s)
1[a]	SF1	0.74 m²/L	21	0.95	0.88	0.92	0.38	40	13	0.33	5.6
2[a]	SF1	0.98 m²/L	21	3.27	1.28	0.39	0.55	57	15	0.26	6.4
3[a]	SF1	1.23 m²/L	14	6.08	1.59	0.26	0.83	55	8	0.15	4.4
4	SF1	1.23 m²/L	7	3.38	1.00	0.30	0.75	50	11	0.23	8.5
5[a]	SF1	1.47 m²/L	14	9.65	2.86	0.30	1.50	56	13	0.24	7.1
6	SF1	1.47 m²/L	7	5.33	2.09	0.39	1.55	57	15	0.27	11.4
7	SF2	0.74 m²/L	7	0.89	0.19	0.22	0.14	76	15	0.19	10.8
8	SF2	0.74 m²/L	7	2.03	0.67	0.33	0.49	71	15	0.21	11.0
9	SF2	0.74 m²/L	7	3.12	0.70	0.22	0.51	76	13	0.17	9.8
10	SF2	0.98 m²/L	7	7.85	3.19	0.41	2.36	63	13	0.21	9.9
11	SF2	0.98 m²/L	7	11.34	1.02	0.09	0.76	66	18	0.27	13.2
12	SF2	0.98 m²/L	7	14.36	3.53	0.25	2.61	67	15	0.23	11.4
13	SF2	1.23 m²/L	7	9.88	2.01	0.20	1.49	54	9	0.16	6.4
14	SF2	1.23 m²/L	7	16.12	5.09	0.32	3.77	53	7	0.13	5.3
15	SF2	1.23 m²/L	7	52.83	8.30	0.16	6.15	64	14	0.21	10.2
16[a]	SF2	1.47 m²/L	14	53.53	8.66	0.16	4.54	57	15	0.26	7.9
17	SF2	1.47 m²/L	7	128.12	19.35	0.15	14.33	58	14	0.25	10.7
18[a]	E1	0.74 m²/L	14	0.21	0.08	0.38	0.04	7	3	0.49	1.7
19	E1	0.74 m²/L	7	0.08	0.02	0.30	0.02	10	6	0.63	4.6
20[a]	E1	0.98 m²/L	21	0.13	0.04	0.33	0.02	10	6	0.63	4.6
21[a]	E1	1.47 m²/L	21	0.55	0.14	0.26	0.06	18	8	0.42	3.3
22[a]	E2	1:1	na	0.00	na	na	na	na	na	na	na
23[a]	E2	1.5:1	8	1.14	0.53	0.46	0.37	78	34	0.43	23.6
24	E2	1.5:1	5	2.62	0.67	0.26	0.59	77	14	0.18	12.3
25[a]	E2	2:1	6	9.04	2.82	0.31	2.25	75	23	0.31	18.7
26	E2	2:1	4	25.4	5.89	0.31	5.77	55	4	0.07	3.8
27[a]	E2	4:1	5	345.60	54.24	0.16	47.5	47	6	0.13	5.3
28[a]	$CaCl_2$	Refer to	10	0.38	0.29	0.77	0.18	50	9	0.18	5.7
29	$CaCl_2$	Table 1	5	1.28	0.53	0.41	0.46	66	5	0.08	4.4

Notes: std = standard deviation, CV = coefficient of variation, 95% CI = 95% confidence interval, na = not applicable, [a]Statistical characterization for the application

Abrasion of product E2 at a 1:1 application (refer to result number 22 in Table 3) resulted in minimal abraded material. The mass abraded was far below the amount required to determine total PM_{10} mass following the methodology. Hence, $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ equals zero for this application. Comparisons of $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ resulting from mold replicate treated with product SF2 applied at 0.74 m^2/L by a one-way ANOVA test indicate that $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ are significantly different between the three molds tested at a 0.05 significance level (refer to results numbers 7, 8, and 9 in Table 3). This result is also the case for molds treated at 0.98 m^2/L and 1.23 m^2/L (refer to result numbers 10 through 15 in Table 3). Following the section of the methodology that describes how to address differences in $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values between the mold replicates, these tests would have to be repeated. For the work presented here, these tests were not repeated but included in Table 3 to illustrate the variability in $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ between mold replicates that can occur, which highlights the aggregate compaction challenges discussed previously. These results will not be used further in the analysis of the methodology.

Comparing Effectiveness of Different Palliatives

The comparative evaluation of products SF1 and E1 illustrates the methodology's ability to differentiate the effectiveness of various palliatives. These applications are numbered 1 and 18 in Table 3. Both products were applied to laboratory-prepared aggregate surfaces compacted in CBR molds (as detailed in Table 2) at an application rate of 0.74 m²/L (30 ft²/gal). Each product was tested on three separate mold replicates, resulting in a total of six molds. Following a two-week curing period, abrasion testing was conducted. Measurements of sample $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ were performed on seven sample runs per mold, yielding 21 data points per product.

A one-way analysis of variance (ANOVA) was conducted to statistically assess the $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values for each set of mold replicates as described in the method section. No statistically significant differences were observed among the $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values for the three mold replicates treated with product SF1 at a significance level of 0.05 (p = 0.12). From Table 3, $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ equals 0.95 µg and the mean $t90^S$ value for the application, $\overline{t90}^a$, equals 40 s. In contrast, the $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{m}}$ values for product E1 indicated statistically significant differences between one mold replicate and the other two (p = 0.002). The statistical characterization results for this statistically different mold replicate are labeled result number 19 in Table 3. The inconsistent mold replicate data was excluded from further analysis. The value of $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ and $\overline{t90}^a$ determined from the two similar mold replicate results equals 0.21 µg and 7 s, respectively.

Statistically comparing the mean of the grouped values of $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ for each application, $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$, using a two-sample t-test (single tail and equal variance) indicates a significant difference between $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ for each application at the 0.05 significance level (p-value = 0.002). The comparison of the palliatives can further be demonstrated by selecting a representative replicate for each palliative, based on $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ values similar to the mean $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ for each palliative and comparing the measured concentrations and $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ as a function of analysis time, C(t) and $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}(\mathrm{t})$, respectively. The C(t) and $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}(\mathrm{t})$ curves for each chosen replicate and their individual values of $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ and $t90^S$ are shown in Figure 5a. For comparison, Figure 5b shows C(t) and $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}(\mathrm{t})$ for an abraded sample testing results obtained from an untreated aggregate sample.

The first noteworthy result shown in Figure 5 is the ability of both palliatives to retain PM_{10} sized particles in the aggregate's surface layer in response to abrading forces. Both palliatives were able to decrease the measured values of total PM_{10} mass by greater than 99.9% from the estimated value measured in the control (Figure 5b). This reduction results in a potentially significant decrease in PM_{10}

emissions from unpaved road surfaces treated with either of these palliatives. Given the considerable contributions unpaved road dust makes to the total mass of PM_{10} emitted to the atmosphere annually, discussed previously, this result shows the vital contribution dust palliatives can have on decreasing the annual PM_{10} emissions.

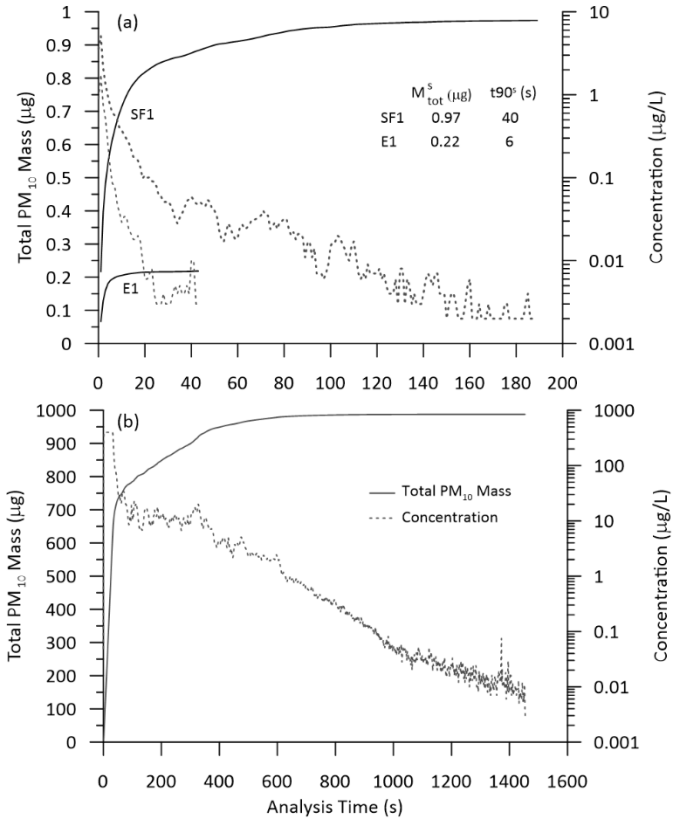

Figure 5. *Comparison of different palliatives applied at the same application rate (a) and results from an untreated sample (b).*

The results shown in Table 3 and Figure 5a for these two products clearly show the test methods ability to distinguish between palliative effectiveness. In this case the emulsion product (E1) was able to retain both the larger and smaller aggregate particles in the treated aggregate surface more effectively than the synthetic fluid product (SF1) as shown the values $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ and $\overline{t90}^{a}$ for both products. Statistically comparing $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ determined for each palliative with a two-sample t-test indicates that the mean values are significantly different at a 0.05 significance level (p values = 0.001).

Comparing the Effectiveness of Different Application Rates

The ability of the methodology to distinguish the effectiveness of a palliative applied to an aggregate surface at different application rates can be demonstrated in the same fashion as previously used to show the methodology's ability to distinguish between palliatives. Two different palliatives are used for this demonstration, SF1 and E2. The performance of the product SF1 was compared at four different application rates: 0.74 m²/L, 0.98 m²/L, 1.23 m²/L, and 1.47 m²/L. In Table 3, the results numbers for each SF1 application rate used for this comparison are 1, 2, 3, and 5. The product E2's performance was

compared at the application rates, 1:1, 1.5:1, 2:1, and 4:1, which are results numbers 22, 23, 25, and 27 in Table 3, respectively.

Each application rate of SF1 was applied to sets of three separate molds compacted with the laboratory prepared aggregate. Similarly, each application rate of E2 was applied to sets of three molds compacted with the field obtained aggregate (refer to Table 2). The test methodology was followed as described previously.

Figure 6 shows C(t) and $M_{tot}^{s}(t)$ results for replicates with the closest M_{tot}^{s} values to the applications' mean, $\overline{M}_{tot}^{a}$. Figure 6b does not include the results from testing the application of the product E2 at a 1:1 application rate. The application rate of 1:1 resulted in such an effective bonding of the surface soils that no sample was able to be abraded off the top of the treated surface. Thus, an application of 1:1 of this product resulted in a value of $\overline{M}_{tot}^{a}$ equal to zero, as previously discussed. Replicate results from testing E2 at a 4:1 application rate is also not shown in Figure 6b owing to the high value of the mean $\overline{M}_{tot}^{a}$ measured for this application.

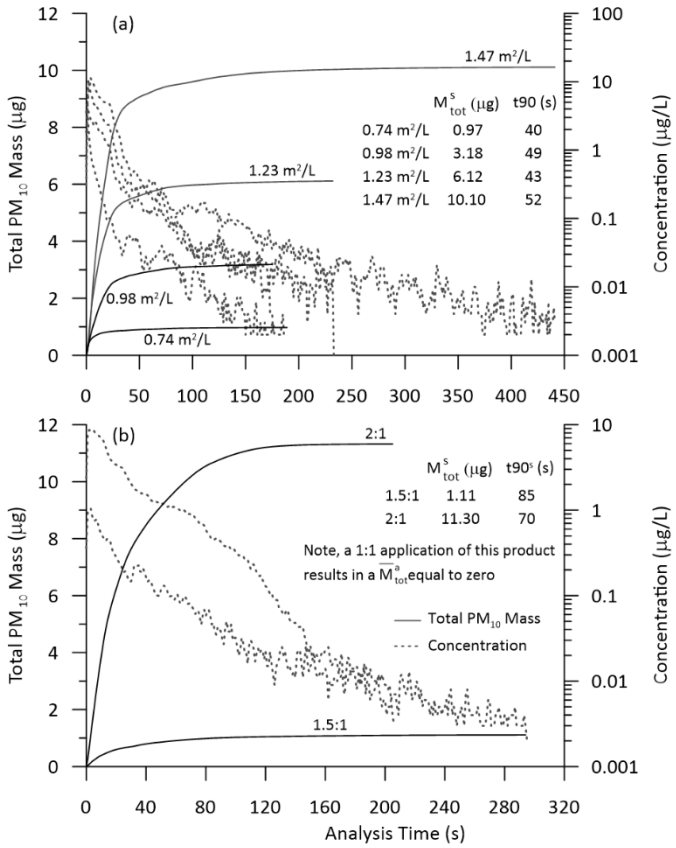

Figure 6. *Comparison of products applied at different application rates. Palliative SF1 shown in (a) and palliative E2 shown in (b).*

Statistical comparisons (two-sample t test) of the mean $\overline{M}_{tot}^{a}$ values determined for each application of each product indicate that the means are statistically different at the 0.05 significance level. Calculated p-values for each comparison are all less than $2x10^{-4}$. These results show the ability of the test methodology to compare the performance of palliatives at different application rates. In this case, application of E2 at a 1:1 application rate with a $\overline{M}_{tot}^{a}$ value equal to zero clearly provides the greatest ability to retain PM_{10} particles in the aggregate's surface layer. An application rate of 0.74 m^2/L of the SF1

product provides the best performance in comparison to lower application rates of this product. For a road manager, these types of data and analysis will be helpful as they make decisions on which products best control dust emissions from their unpaved roads.

Comparison of Products Tested

Table 3 presented previously provides the statistical characterization of all the dust palliatives tested by this methodology so far. The coefficient of variation (CV) in $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ for each of the results shown in Table 3 are less than one with 90% of the results having CV less than 0.41. Similarly, each test of an application also resulted in low CV values for t90^{s}. This consistently low variation in both $\mathrm{M}_{\mathrm{tot}}^{\mathrm{s}}$ and t90^{s} show that this test methodology is very repeatable. Using only the results in Table 3 that are representative of the applications, the effectiveness of the different palliatives can be compared as shown in Figure 7.

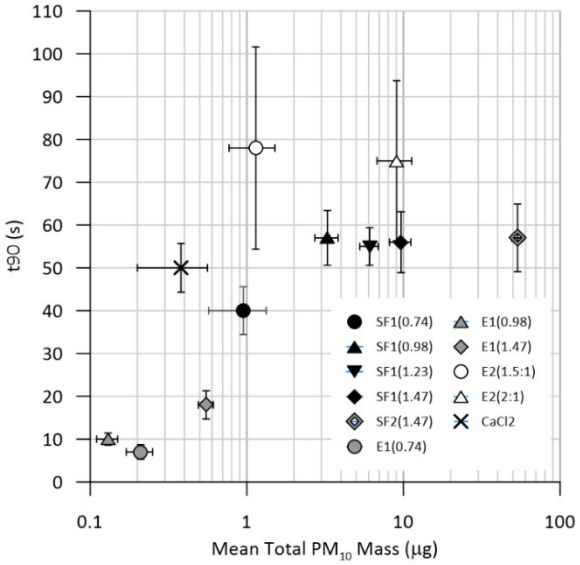

Fig. 7. *Comparison of all palliatives evaluated (error bars show 95% confidence intervals).*

Figure 7 illustrates notable results. As expected, applications of greater amounts of palliative to an aggregate-surface results in better palliative performance in comparison to lighter applications. An exception to the result is the application of product E1 at 0.74 m^2/L and 0.98 m^2/L. The lower application of the product (0.98 m^2/L) resulted in better performance in comparison to the higher. Both applications result in the lowest values of $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ and $\overline{t90}^{a}$ of the different products and applications tested, excluding the 1:1 application of product E2, which produced almost no material when abraded. These results represent the lower limits expected for $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ and $\overline{t90}^{a}$ using this test methodology.

For all the applications evaluated, it appears that $\overline{t90}^{a}$ has an upper limit of around 80 s. Of the palliatives tested, the applications with the lowest $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ values have $\overline{t90}^{a}$equal to 50 s or less. Additional testing is required to determine an acceptable value of $\overline{t90}^{a}$ in relation to $\overline{\mathrm{M}}_{\mathrm{tot}}^{\mathrm{a}}$ for a well performing palliative.

The results presented clearly show the ability of the test methodology to discern the effectiveness of different palliatives and different palliative application rates to retain PM_{10} particles in the surface aggregates of unpaved surfaces. These results validate the resolution of the test methodology.

Limitations of the Methodology

The purpose of this test methodology is to evaluate and compare the effectiveness of dust palliatives based on their ability to retain PM_{10} sized particles in the upper surface of an aggregate subject to abrading forces. Palliatives with greater PM_{10} retention capabilities will provide adequate dust control for a reasonable period. However, the test does not provide a rigorous evaluation of a palliatives longevity once applied to an aggregate surface. The longevity of dust palliative performance is based on factors such as average daily traffic, prominent types of vehicles the unpaved road supports (mining trucks versus light vehicles for example), road design, among other factors. Testing the longevity of a dust palliative applied to an unpaved road is best accomplished by field testing palliative applications over time. This methodology can be used for such field testing by obtaining and testing field-abraded samples from the treated surface periodically and assessing decreases in dust control performance.

As previously mentioned, experience has demonstrated that meticulous preparation of the sample is a critical step in the testing methodology. In many instances, the porosity of the surface impacts the test results. Therefore, it is essential to ensure a uniform surface across all replicates. This necessitates thoroughly mixing an adequate quantity of soil to prepare all replicates being tested. The removal of soil from the storage container must be conducted in such a way as to prevent segregation. The surface should be carefully finished to maintain uniformity across all replicates.

Conclusion

The lack of a predictive test to determine the effectiveness of dust palliatives applied to unpaved surfaces forces road managers to decide on dust control strategies by trial and error. The simple test methodology presented here provides road managers with the predictive capability required. Evaluation of the test methodology shows the test to be repeatable. The results also show the test has the resolution necessary to compare the effectiveness of different palliative products and different application rates. Evaluation of different palliative products and different application rates using this methodology will help increase the overall understanding of palliative performance, which will benefit both palliative producers and road managers.

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Appendix A

Dust Palliative Performance Test

1. Scope

This method describes the procedure for determining the *total PM_{10} mass* for dust propelled into a dust column device. The purpose is to quantify the effectiveness of dust palliative on aggregate surface course.

This standard involves hazardous materials, operations and equipment. This standard does not purport to address all the safety problems associated with its use. It is the responsibility of the agency to establish appropriate safety and health practices and to train the user of this standard prior to use. It is the responsibility of the user to consult the appropriate agency authority for and to practice and maintain the appropriate safety and health practices.

2. Apparatus

- Testing apparatus conforming to the design shown in Figure A-1 through Figure A-4.
- Sieves # 4 and # 8 conforming to AASHTO M 92 (ASTM E 11).
- Balance or scale: Class G1, sensitive to 0.01 g with a capacity sufficient for the principle sample mass, and meeting the requirements of AASHTO M 231.
- Abrader (Figure 1) with 80-grit sandpaper, and with ten-pound weight (for laboratory sample testing), and fifteen-pound weight (for field sample testing).
- Compaction mold and collar (6 inch) conforming to ATM 207 (AASHTO T 180), or CBR mold and collar (6 inch).
- Graduated pipet with metered pipet pump.
- Cans/tins with covers, having a minimum volume of 100 ml and capable of holding 100 grams.
- Containers made of material resistant to corrosion and impervious to moisture, having close-fitting lids to prevent loss of moisture from soil samples before compaction.
- Miscellaneous tools, materials, and equipment including spatulas, putty knife, soft bristle brushes, pan, parchment paper, laboratory grade acetone, microfiber cloth, Plexiglas column including base and pressure vessel, intake tube, *DustTrak II Aerosol Monitor 8530* or equivalent.

3. Soil Sample Preparation

3a – Method A (Field-Obtained or Laboratory-Prepared Aggregate Sample)

1. For field-obtained sample test, obtain field sample according to ATM 301. Go to Section 4 to continue test procedure.
2. For laboratory-prepared sample test, perform ATM 207 (AASHTO T 180) on the soil/aggregate sample to determine optimum moisture content.

3. Dry a separate soil/aggregate sample to constant mass in accordance with ATM 202.
4. Sieve over #4 sieve and discard material retained on #4 sieve.
5. Thoroughly mix the selected representative sample with sufficient water to dampen it to approximately 70% of optimum moisture content (± 5%) as determined by ATM 207 (Step 2 above).
6. Place the prepared material in the mixing/storage dish, check its consistency (adjust if required), cover to prevent loss of moisture, and allow to saturate for at least 16 hours (overnight). After this standing period and immediately before starting the test, thoroughly remix the soil. Start the test within 36 hours of end of saturation period.
7. Compact the soil sample in 6-inch diameter Proctor or CBR mold in accordance with ATM 207.
8. Determine the quantity/volume of palliative to be applied using the following expression:
   Volume (ml) = 82.58 x Field Application Rate (sq.yd./gallon), or
   Volume (ml) = 743 x Field Application Rate (sq.ft./gallon).
9. Apply the quantity of palliative evenly over the surface of the compacted soil.

   Note 1: This may require multiple applications allowing the palliative to soak in between applications.
10. Allow to maturate at room temperature in open air for fourteen days. If in a dusty environment cover with breathable cloth or move to dust-free environment. Go to Section 4 to continue test procedure.

3b – Method B (Field-Abraded Sample)

1. Select locations on palliative treated section to obtain field abraded samples.
2. Carefully sweep loose aggregate from the sample location using a soft brush.
3. Place the abrader base plate guide on the sample location (Figure A-4)
4. Attach an 80-grit sandpaper disc to the bottom of the abrader.
5. Load the abrader with 15-lbs weight.
6. Place the abrader in the circular hole in the abrader guide.
7. Turn the abrader 10 full clockwise rotations without exerting downward pressure.
8. Tilt the abrader on edge and carefully brush loose material off the bottom of the abrader back into the abraded area.
9. Using a soft bristle brush and a putty knife, collect the abraded material from the abraded area and place the material into a moisture can.
10. Replace the abrader into the hole in the abrader guide and repeat steps 6-9 until moisture can is approximately one-half full of sample.

11. Seal the can with electrical tape and label the can for content.
12. Repeat steps 1 through 11 (Method B) at other selected locations.
13. Proceed to Section 4 (Soil Sample Abrasion), step 8.

4. Soil Sample Abrasion

1. After fourteen days of maturation of the laboratory-prepared specimen, place the compaction collar on the mold.
2. Cover a pan with parchment paper and place the mold in the pan.
3. Attach an 80-grit sandpaper disc to the bottom of the abrader.

   Note 2: Use new sandpaper for each tested specimen.
4. For laboratory-prepared specimens, load the abrader with a 10-lbs weight.
5. Place the abrader on top of the soil in the mold.
6. Apply ten full clockwise rotations of the abrader without exerting downward pressure.
7. Clean the abraded soil surface and the sandpaper using a soft bristle brush, avoiding breakdown and the loss of fines.
8. Gently sieve the abraded material over the #8 sieve over the parchment paper, taking care not to break down the soil and to prevent material from becoming airborne. Materials retained on the #8 sieve may be discarded.
9. Repeat steps 4 through 6 until a minimum of 40 grams of material passing the #8 sieve have been collected. Limit rotations to twenty revolutions (ignore step if field-abraded sample).
10. Place the material passing the #8 sieve in a moisture can carefully to ensure the soil is not broken down.
11. Seal the can with electric tape and label the can for content.

5. Sample Chamber Preparation

1. Clean the sample chamber using a clean cloth dampened with acetone to remove any residual palliative.
2. Close the pressure chamber valve.
3. Using a bicycle pump, pressurize the pressure chamber to 20 psi.

Note 3: The pressure may be adjusted using the bleed valve.

6. Dust Column Preparation

1. Remove the intake tube from the column.
2. Carefully clean the interior of the dust column with a slightly dampened microfiber cloth.

3. Install the intake tube into the column.
4. Place the *DustTrak* device on the table facing the intake tube and attach it to the intake tube.

   Note 4: Ensure rubber hose is almost horizontal. Note that the hose length is not critical.

7. Procedure

1. Carefully open the moisture can (Step 11 in Section 4) and gently mix the sample to achieve a uniform sample.
2. Quarter the sample by scoring two orthogonal lines through the sample
3. Place an empty weighing tin on the balance and tare it. Weigh 2.0 grams of sample (+/- 0.005 g) taking small portions from each quarter until the required 2 grams have been collected
4. Carefully place the sample in the sample chamber ensuring all of the material is placed in the chamber.
5. Place the column on the sample base with the intake hole on the bottom.
6. Place the cap on top of the column.
7. Using the pump, set the chamber pressure to 20 psi.
8. Zero the *DustTrak* using the procedure outlined in its manual and let it run for one minute.

   Note 5: *R*eview the *DustTrak* manual for operating instructions.

9. Install the PM_{10} impact filter
10. Set the sample interval to 1 second on the *DustTrak*
11. Set the testing time using these guidelines:

a. 7 minutes for a treated sample expected to work well

b. 15 minutes for a sample that is anticipated to have marginal performance

c. 1 hour for an untreated sample

   Note 6: It is recommended to program longer time if in doubt and stop the test once background has been reached.

12. Start the *DustTrak* in in mode to record data and allow it to run for at least thirty seconds to obtain a background level. This measurement will be used in the analysis and included in the test report.

    Note 7: During background measurement watch the view screen on the DustTrak and estimate the background concentration from the data displayed on the screen.

    Note 8: Do not stop the *DustTrak* before opening the pressure valve. If the background level exceeds 0.006 mg/m^3 either use a dust filter in the room or move to a space which has a background level below 0.006 mg/m^3.

13. Open the pressure chamber release valve after thirty seconds.
14. Allow the test to run for programmed time or to the estimated background concentration is reached (see Note 7).
15. Download the data onto a flash drive to transfer to a computer for analysis.

8. Calculations and Data Analysis

1. Import the test data into a spreadsheet.
2. Open the test data in a spreadsheet. This spreadsheet is called the raw data spreadsheet for the sample run.
3. From the raw data spreadsheet, locate the first concentration value that exceeds estimated initial background concentration measurements by at least one-order of magnitude (see Note 7). Referring to the example data shown in Figure A-5, the concentration value at 33 seconds (0.03 mg/m^3) would be selected. This value is the initial particle settling concentration measurement after the sample is propelled into the column, C_0.
4. Calculate the background concentration in the column, C_b, by averaging the fifteen concentrations prior to C_0 recorded in the raw data spreadsheet. Record this value to the nearest thousandth using the standard rules for rounding numbers.
5. Subtract C_b from each recorded concentration beginning with C_0 and ending at the first occurrence of a recorded concentration equaling C_b (refer to Equation 1).

$$\acute{C}_\imath = C_i - C_b \qquad (3)$$

   $\acute{C}_i$ equals the concentration at timestep i minus the background concentration, C_i equals the concentration measured in the column during particle settling at time step i, and C_b equals the average background concentration in the column prior to projecting the sample into the column.

6. Beginning with the concentration following C_0, C_1, calculate the total mass measured for the sample run ($M^s_{tot,j}$) using the following equation:

$$M^s_{tot,j} = \sum_{i=1}^{i=n} \left(\frac{\acute{C}_{\imath-1} + \acute{C}_\imath}{2}\right) \cdot Q_{air} \cdot \Delta t \qquad (4)$$

   Q_{air} is the flow rate of the air pulled through the nephelometer (1.0 L/min), Δt equals sampling interval (1.0 s), and n equals the number of time steps recorded prior to reaching the first measured background concentration, j equals the sample run number (1 through 5).

7. Determine the time from the start of the particle settling phase required to reach 90% of the total mass determined in step 6 for the sample run using the following equation

$$t90^s_j = 0.90 \times M^s_{tot,j} \qquad (5)$$

8. Repeat steps 1 through 7 for each of the five sample runs per mold.
9. Calculate the average total mass for the mold replicate ($\overline{M}^m_{tot,k}$) using the following equation

$$\bar{M}_{tot,k}^{m} = \frac{\sum_{j=1}^{5} M_{tot,j}^{s}}{5} \quad (6)$$

k is the mold replicate number, 1, 2 or 3.

10. Use the following equation to determine the mean t90 value for the mold

$$\overline{t90}_{k}^{m} = \frac{\sum_{j=1}^{5} t90_{j}^{s}}{5} \quad (7)$$

11. Repeat steps 1 through 10 for each mold replicate.

12. Using one-way (also referred to as single factor) analysis of variance (ANOVA) compare the results from each mold replicate at a 0.05 significance level. If there is no significant difference between the values $\bar{M}_{tot,k}^{m}$ according to the ANOVA results, determine the mean mass total for the application, $\bar{M}_{tot}^{a}$, using the following equation

$$\bar{M}_{tot}^{a} = \frac{\sum_{k=1}^{3} \bar{M}_{tot,k}^{m}}{3} \quad (8)$$

Note 9: Use of Microsoft Excel or similar program is recommended to conduct ANOVA analysis

13. Use the following equation to determine mean t90 for the application

$$\overline{t90}^{a} = \frac{\sum_{k=1}^{3} \overline{t90}_{k}^{m}}{3} \quad (9)$$

14. If the ANOVA analysis indicates a significant difference between the values of $\bar{M}_{tot,k}^{m}$, perform two-sample t-tests (single tail and equal variance) to determine which values of $\bar{M}_{tot,k}^{m}$ are significantly different at a 0.05 significance level. If $\bar{M}_{tot,k}^{m}$ for one mold is different than the other two, determine the mean mass total for the application, $\bar{M}_{tot}^{a}$, from the results of the significantly similar values of $\bar{M}_{tot,k}^{m}$ using the following equation

$$\bar{M}_{tot}^{a} = \frac{\sum_{k=1}^{2} \bar{M}_{tot,k}^{m}}{2} \quad (10)$$

Note 9: Use of Microsoft Excel or similar program is recommended to conduct t-test analysis

15. For the case where the $\bar{M}_{tot,k}^{m}$ values are similar for only two molds, using the values for $t90_{k}^{m}$ determined in step 10 for these two molds, calculate the t90 for the application using the following equation

$$\overline{t90}^{a} = \frac{\sum_{k=1}^{2} \overline{t90}_{k}^{m}}{2} \quad (11)$$

16. If the ANOVA analysis followed by t-test analysis indicates the values of $\bar{M}_{tot,k}^{m}$for all three molds are significantly different, repeat the test starting with step 3a

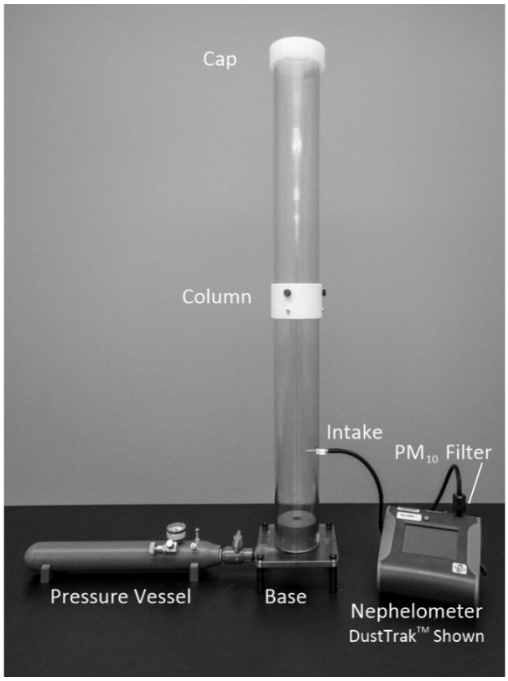
9. Report

Report the following:

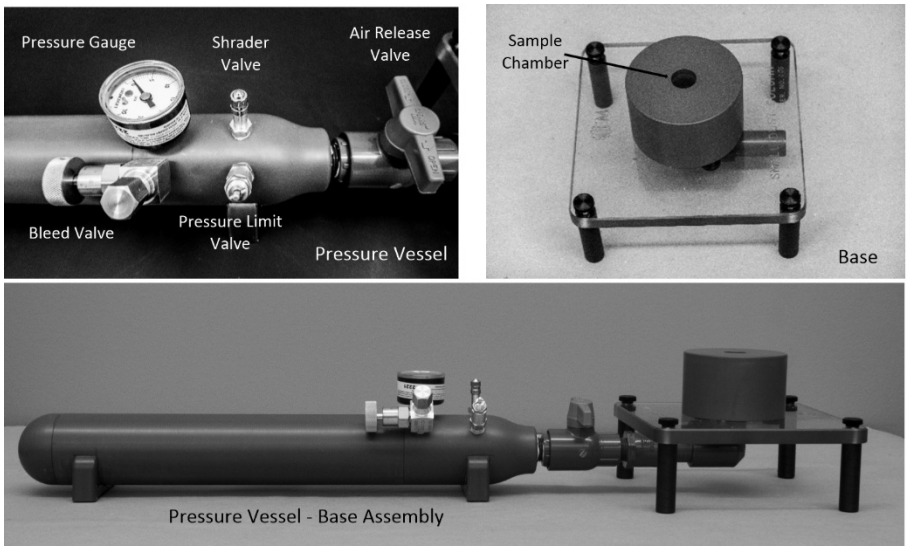
1. The type, source, description and classification of the soil tested.

2. The type, name, source and concentration of the palliative used, if any

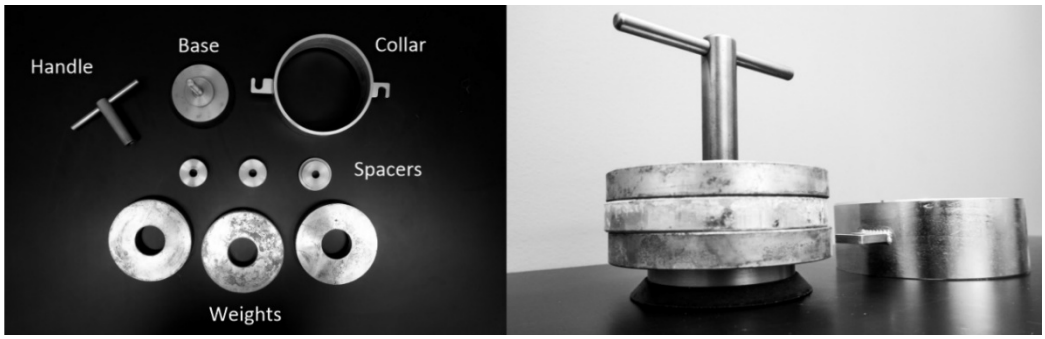
3. The values of the mean total PM_{10} mass $\bar{M}_{tot}^{a}$ and $\overline{t90}^{a}$ for the application.



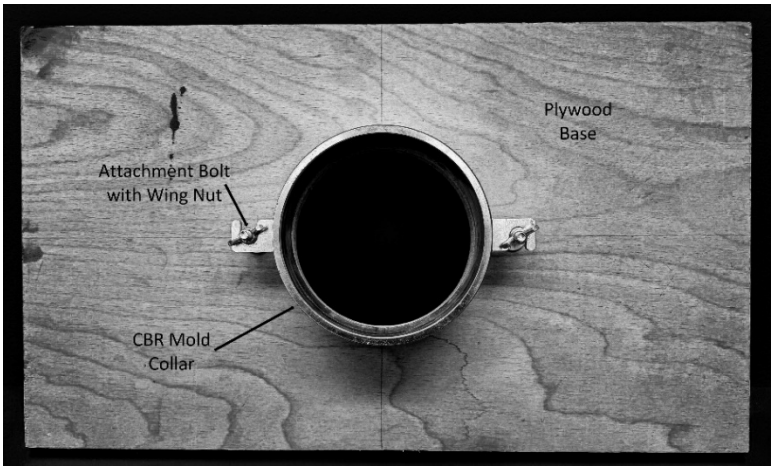
A-1. Column Apparatus



A-2. Pressure vessel and base assembly



A-3. Abrader



A-4. Abrader base plate guide for field abrasion

	Elapsed Time [s]	Mass [mg/m3]
20		
21	1	0.001
22	2	0.001
23	3	0.001
24	4	0.001
25	5	0.004
26	6	0.001
27	7	0.001
28	8	0.001
29	9	0.001
30	10	0.001
31	11	0.001
32	12	0.001
33	13	0.001
34	14	0.001
35	15	0.001
36	16	0.001
37	17	0.001
38	18	0.001
39	19	0.001
40	20	0.001
41	21	0.001
42	22	0.001
43	23	0.001
44	24	0.001
45	25	0.001
46	26	0.001
47	27	0.001
48	28	0.001
49	29	0.001
50	30	0.001
51	31	0.001
52	32	0.001
53	33	0.03
54	34	2.46
55	35	5.14

A-5. Example concentration data output file