FIXATIVE ANALYSIS FOR SOIL STABILIZATION ACTIVITIES AT HANFORD (TASK #3)

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EXECUTIVE SUMMARY

The experimental work described in this report was conducted in support of the Department of Energy's (DOE's) Washington Closure Hanford Field Remediation Project at DOE's Hanford site and had the purpose of assessing the performance of commercially available fixatives and their ability to control erosion of soil mounds when exposed to a range of wind forces. This report details the results obtained during the execution of wind tunnel and depth penetration studies conducted at the Applied Research Center (ARC) at Florida International University (FIU). These experiments were conducted between May and November 2006. Over 600 soil samples, weighing approximately 224 grams and shaped in the form of a "mound," were used during the wind tunnel experiments. Over 500 pounds of uncontaminated soil was obtained and shipped to FIU from the Hanford site. The Hanford soil was used to prepare representative soil samples used during the wind tunnel and depth penetration experiments. The Hanford soil was analyzed and classified as **SP** for a sandy cohesionless poorly graded soil (> 96% sand); therefore, throughout this paper the soil obtained from the Hanford site is referred to as Hanford SP soil. The soil samples were prepared by varying the percent moisture of the soil matrix (between 2.7% and 20% by weight) and by spraying and/or pouring the selected fixatives onto the soil samples containing an initial moisture content of 2.7% by weight. Also, cerium oxide (CeO_2) was mixed with soil samples to simulate Plutonium (Pu) powder contamination. After the soil samples were prepared, the soil samples were placed in an open loop, low-speed wind tunnel and exposed to wind forces ranging from 10 to 30 miles per hour (mph). The purpose of the wind tunnel experiments was to identify the effects of wind erosion on the soil samples, by calculating the amount of soil displacement due to wind forces, by recording PM10 concentrations generated during the process, and by measuring the changes in soil moisture during the experiments. Also, the emission/dispersion characteristics of Pu powder contamination, via cerium oxide simulant, were quantified and analyzed during the experiments. For the wind tunnel experiments, three commercially available fixatives were selected and tested. These fixative include a calcium chloride solution (RoadMaster™), a petroleum hydrocarbon emulsion (DustBond®), and a synthetic organic (DuraSoil®).

The results from this study showed that the amount of soil displaced and the amount of PM10 concentrations increased as the wind velocity increased from 10 to 30 mph. A

significant increase in soil displacement was observed for soil containing 2.7% moisture when exposed to wind velocities in the range of 15 to 25 mph. similar trends were observed for soil samples with higher moisture content, such as, 5%, 10%, 15%, and 20%. The experimental results also indicated that moisture content in the soil played a significant role in the soil's ability to withstand erosion when exposed to varying wind velocities. It was demonstrated that there was a substantial reduction in soil displacement when the moisture in the soil increased from 2.7% to 20%. PM10 particle size measurements were also collected and analyzed for Hanford's SP soil with varying moisture content (2.7% - 20%) exposed to a velocity range of 10 to 25 mph. The largest concentration (240.220 mg/m^3) was recorded for the Hanford's SP soil with 2.7% moisture at a velocity of 25 mph. The amount of PM10 generated changed with decreasing wind velocity. For example, for the same soil moisture (2.7%) and a wind velocity of 15 mph, the average PM10 concentration decreased to 8.716 mg/m^3. It was also observed that as the soil moisture increased, the PM10 concentration decreased. For example, for the same velocity of 15 mph but at 20% moisture, the PM10 concentration was reduced to only 0.103 mg/m^3.

As indicated above, three commercially available fixatives products were applied to the soil samples during the wind tunnel experiments. Overall, it was demonstrated that the selected fixatives provided good results. The wind tunnel experiments showed no soil movement when manufacturer's recommended dilution and application rates were used. Based on these preliminary results, additional dilution ratios and application rates were calculated and used for subsequent wind tunnel experiments. Only two fixatives (DustBond® and DuraSoil®) were tested at their manufacturer's recommended dilution ratios and application rates (i.e. 7.0:1.0 and 100% AR respectively). When comparing these two fixatives (DustBond® and DuraSoil®), the DustBond® fixative showed better performance in suppressing PM10 concentrations. This can be seen by comparing the highest dilution ratios and application rates of DustBond® and DuraSoil® at the maximum wind velocity of 30 mph. At this wind velocity, the PM10 concentration for DustBond® is very low (0.400 mg/m^3) when compared to the results obtained for DuraSoil® (1.480 mg/m^3) at the same wind velocity. When comparing the results of DustBond® with the results of RoadMaster™ highest dilution ratio (10%), it was seen from the data that DustBond® performed better than RoadMaster™ (0.400 mg/m^3 vs. 0.615 mg/m^3 at 30 mph). It is evident from the data that the amount of PM10

generated increased as the velocity increased; this is true for all the three fixatives tested. The performance of the fixatives was comparable to results obtained for Hanford's SP soil with higher percent moisture, mainly 10%, 15%, and 20%. For all these cases, very little soil (0-4 grams) was displaced.

As indicated above, cerium oxide was used to simulate Pu powder contamination in the soil. The experiments showed an increase in the amount of soil displacement and the amount of PM10 concentrations when cerium oxide was mixed with the soil (with and without fixatives). PM10 concentration of 279.095 mg/m^3 was obtained for Hanford's SP soil with initial 2.7% moisture at 20 mph. This is a 16% increase when compared to the Hanford's SP soil without cerium oxide simulant added to the soil (240.220 mg/m^3). Similar trends were observed for the other soil matrices (i.e., soil sprayed with fixatives) used in the wind tunnel experiments.

The penetration depth studies helped to better understand the penetration characteristics of the fixatives as a function of time and moisture content in the soil. For these experiments, a fourth (TACPAC GT) fixative was selected and tested. It was demonstrated that fixatives DustBond® and DuraSoil® provided very good results for the moisture levels tested (1.2%, 2.7%, 3.7%, 5.3%, and 7.7%). On the other hand, RoadMaster™ and TACPAC GT did not perform as well. For a twenty-hour penetration depth application period at 7.7% moisture, the highest penetration depths achieved were approximately 4.5 and 3.0 inches for DuraSoil® and DustBond®, respectively. In the case of RoadMaster™ and TACPAC GT, the penetration depths achieved during the same experiment were approximately 1.1 and 0.45 inches, respectively.

Section 5 of this report presents detailed results and discussions on all the experiments conducted in this study. Conclusions to this study are presented in Section 6.

1.0 INTRODUCTION

Part of the Department of Energy's (DOE's) environmental management mission at the Hanford site includes characterizing and remediating contaminated soil and groundwater; stabilizing contaminated soil; remediating disposal sites; and decontaminating, decommissioning, and demolishing former plutonium production process buildings, nuclear reactors, and separation plants. The Hanford remedial program is managing waste from more than five decades of nuclear weapons production. A wide variety of wastes were disposed in burial ground areas and some of these contaminated wastes present the risk of airborne contamination and cross-contamination hazards, especially during excavation and soil removal activities. In order to address and mitigate these hazards, site personnel use a combination of water and surfactants to suppress airborne contaminants during soil remediation and removal activities. The effectiveness of this baseline method is dependant on the quantity of the surfactant and weather conditions, which will limit the performance period based on temperature, humidity, and wind speed. Another issue that greatly influences the importance of contamination control is the type and quantity of the contaminant. The specific burial grounds in question may contain plutonium (Pu) powder, a charged particle with dispersive characteristics. It is vital for the site to control the dispersion of this contaminant when weather conditions are conducive for soil dispersion and therefore the spread of contamination.

The Applied Research Center (ARC) at Florida International University (FIU) supported the Washington Closure Hanford Field Remediation Project at the Hanford site by analyzing the use of several commercially available fixatives products for contamination control (suppression) of dust and soil particles. The study focused on determining the effects of varying environmental conditions, such as moisture and wind forces, on the performance of the selected fixatives.

2.0 TASK OBJECTIVES

The main objective of this study was to conduct a comparative analysis of the soil suppression capability of several commercially available fixative products. The suppression capabilities of these products were tested by wind forces experiments where the wind forces were varied from 10 to 30 mph. The penetration characteristics of these products were tested by conducting depth penetration column studies. Specific project objectives included:

- Selection of several candidate fixatives, based on input from Hanford personnel and performance specifications;
- Determination of the ability of the fixative to suppress the soil matrix and reduce the amount of particle movement when the fixative/soil matrix is exposed to wind forces ranging from 10 – 30 mph;
- Study the effect of soil moisture on the performance of the selected fixative;
- Study the amount of particulate matter (PM10) generated as a function of fixative type, moisture content in the soil, and wind loading; and
- Analysis of the nature of the interaction between the candidate fixative and a plutonium (Pu) powder contaminant simulant (cerium IV oxide (CeO_2))

3.0 EXPERIMENTAL APPROACH AND SETUP

In order to understand the interaction between Hanford SP soil (sandy soil) and commercially available fixatives products, two main experiments were designed and conducted:

- Penetration depth experiments – *penetration depth of various fixatives while varying soil moisture content.*
- Wind force experiments – *wind induced soil loss/displacement and dust generation*

Penetration depth time studies were conducted to identify the mobility of the selected fixatives once applied to the surface of the sandy soil. Column penetration tests were conducted on all selected fixatives as a function of time and soil moisture. Also soil samples, with varying percent moisture and/or fixative ratios, were placed inside a wind tunnel test section and exposed to wind velocities ranging from 10 to 30 mph so that the wind induced soil displacement could be studied. For these experiments, the moisture of the soil was varied from 2.7% to 20% by weight. Also, the sandy soil samples were prepared and sprayed with three selected fixatives and exposed to the same wind velocities. Finally, plutonium contamination on the soil was assessed by using a Pu powder simulant (cerium IV oxide). The quantity of the simulant was varied (from 5% to 20% by weight) so that the effects of wind force, moisture, and fixatives performance could be studied and analyzed during wind tunnel experiments.

3.1 Materials and methods

3.1.1 Fixative selection

An extensive literature search was conducted to identify the different commercially available fixative products used for dust and soil stabilization. Additional information was obtained directly from Hanford personnel. This review evaluated the categories of fixatives and determined which would meet the technical, operational, hazard and disposal requirements laid out by Hanford personnel. Based on this search and discussion with site personnel, several fixative categories were determined to meet the criteria. These categories led to the

selection of fixatives that would be representative of the chosen categories. The fixatives reviewed and selected included: (1) a calcium chloride solution (38% solution); (2) a petroleum hydrocarbon emulsion; (3) a synthetic organic; and (4) an organic polysaccharide. Selection of these fixatives does not mean that the use of other fixatives in the same fixative category should not be used, nor is it an endorsement of the product. In fact, the specific fixatives were chosen because they have been previously tested or evaluated to some degree by Hanford's site personnel. The tests conducted by the Applied Research Center were intended to further enhance site personnel's knowledge-base by looking at parameters not previously tested. It was expected that the data generated by these tests would assist site personnel in making decisions on which category of fixative will work best for their specific application. Table 1 below describes the fixatives selected for this study:

Table 1 Fixative for soil and dust suppression

Name	Type	Chemical Category
RoadMaster™	Fixative	Calcium Chloride (38%)
DustBond®	Capture Coat	Petroleum Hydrocarbon Emulsion
DuraSoil®	Capture Coat	Synthetic Organic
Guar Tackifier*	Capture Coat	Organic polysaccharide

***** The Guar Tackifier was used only for penetration depth studies

3.1.2 Particulate size distribution analysis and soil classification

As an initial step, approximately 500 lbs of uncontaminated soil was obtained and shipped from the Hanford Reservation in Washington State. The soil provided from the Hanford site was collected from an uncontaminated location in the vicinity of the burial ground 618-10. The soil was sampled and tested before released from the site. The test results showed the soil to be uncontaminated. Upon arrival at FIU, a homogenous sample of the Hanford soil was prepared. The particle size distribution analysis of the soil sample was performed by using the Bouyoucos Hydrometer Analysis method [4]. Based on the results from this analysis, it was determined that the Hanford soil contained an average of 96.2% sand, 3% silt, and 0% clay as shown in Table 2.

Table 2 Particle size distribution analysis of Hanford soil

Soil Sample #	Sand (2.0-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)
1	97.5	2.5	0.0
2	82.5	15.0	2.5
3	95.0	5.0	0.0
4	97.5	2.5	0.0
5	95.0	5.0	0.0

Based on the results from the Bouyoucos Hydrometer analysis and the soil textural triangle presented in Figure 1 [15], it was concluded that soil provided by the Hanford Site could be characterized as sandy soil [3]. Based on the Unified Soil Classification (USC) System [16], it was further determined that the Hanford soil can be classified as **SP** for a sandy cohesionless poorly graded soil. In this report, the soil used for these experiments will be referred to as **Hanford's SP soil**.

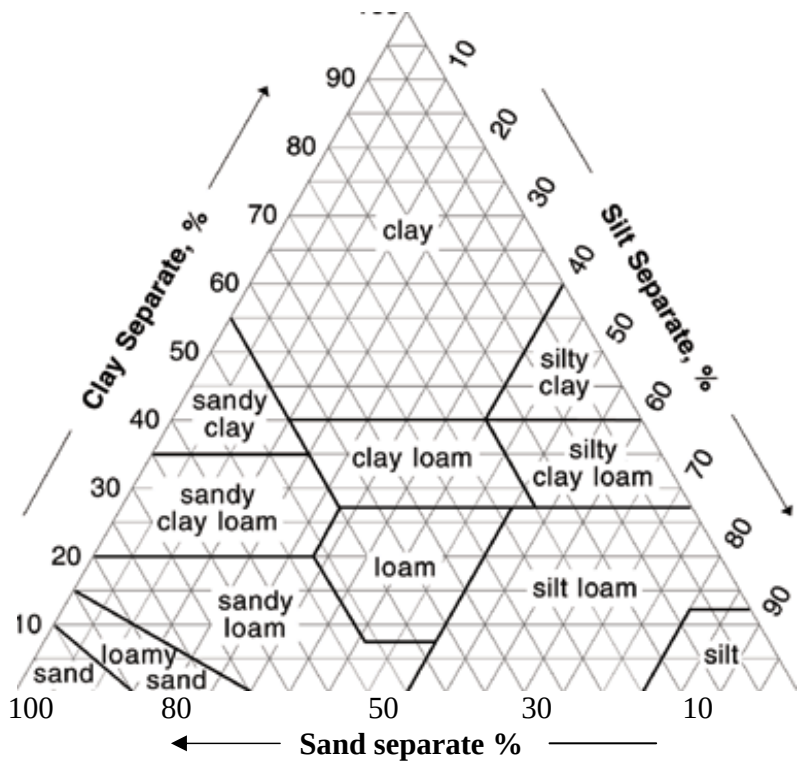

Figure 1 Soil textural triangle [15]

3.1.3 Moisture analysis

The moisture content of the sandy soil was determined by modifying the American Standard for Testing and Material (ASTM) Standard D2216 and was found to be 2.7% by weight. The

analysis was conducted by using an OHAUS/MB200 instrument. Specimens of approximately 2 grams of wet soil were weighed and placed in an oven at 205°C for a period of 4-6 min. Table 3 shows a sample of some of the results obtained during this analysis. For the purpose of this study, this was considered the "baseline" case and assumed for an SP soil. The soil was stored in an airtight container and at room temperature to avoid moisture loss or addition.

Table 3 Soil moisture analysis by OHAUS/MB200 instrument

Sample #	Wet Weight (grams)	Dry Weight (grams)	Moisture (%)	Solids (%)
1	2.53	2.47	2.7	97.3
2	2.52	2.46	2.7	97.3
3	2.51	2.45	2.7	97.3

3.1.3.1 Mass balance and moisture change calculations

A soil mass balance was conducted after each wind tunnel experiment to quantify the amount of soil displaced by the wind forces. As expressed by Equation 1.0, the initial mass of the soil sample, the total mass remaining at the wind tunnel's test section, the total amount of soil used for moisture testing, the total mass collected at the end of the wind tunnel, and the mass lost due to evaporation effects were monitored and recorded for each wind tunnel experiment. The moisture lost was calculated by performing a moisture test before and after the soil sample was exposed to the various velocity profiles. Two small soil samples (approximately 2 grams) were taken after each speed (10 mph, 15mph, 20mph and 25 mph) and analyzed for moisture as described in section 3.1.3 above. The total mass unaccounted for was calculated by using Equation 1.0 shown below:

$$Mass_U \text{ (grams)} = [(A) - (B + C) - D)] \qquad \text{Equation 1.0}$$

Where:

$Mass_U$ = Unaccounted mass

A =Initial soil mass at the beginning of the test, placed in the wind tunnel test section

B =Total mass collected at the wind tunnel test section for all wind velocities

C =Total mass collected at the back end of the wind tunnel and taken for moisture sampling
D =Mass lost due to evaporation (initial mass (A) multiplied by delta in percent moisture)

3.1.4 Particulate matter (PM10) measurements

PM10 concentrations were measured downstream of the wind tunnel test section, the probe was placed approximately one inch behind the soil sample. A real-time dust monitor (TSI 8520 Dust Track) was used to record these measurements. This highly sensitive monitor detects dust and measures PM10, PM2.5 and PM1.0. PM10 refers to particulate matter of particles smaller than 10 μm in diameter; PM2.5 are particulate matter of particles smaller than 2.5 μm in diameter and consequently PM1.0 defines particulate matter of particles smaller than 1.0 μm in diameter. For the purpose of this research work, PM10 particle size measurements were recorded for an average of 10 minutes per experiment. For this study, it was determined that a 10-minute time frame would be sufficient to provide an idea of the amount of airborne particles generated by the wind. These measurements are not intended to provide and/or aid in determining Health and Safety (H&S) risk assessments on the fixative tested, or to calculate 8-hour weighted average data for H&S purposes. Simply, the information gathered for these experiments can provide a quick comparison on the airborne suppression properties of the selected fixative and the suppression of PM10 particulates due to varying soil moisture.

3.1.5 Cerium oxide simulant

Based on literature research and Hanford site personnel recommendation and experience, cerium oxide powder (5 μm particle size) was selected as a simulant to plutonium (Pu) power contamination. The cerium oxide powder was mixed with Hanford's SP soil and fixatives and used in wind tunnel experiments. Cerium oxide (CeO_2) is slightly hygroscopic and also absorbs a small amount of carbon dioxide from the atmosphere. The selected simulant is a very fine, light yellow powder; the transportation characteristics were observed during the wind tunnel experiments. Particulate matter (PM10) data was recorded to quantify the PM10 concentrations generated by the presence of this simulant. Since the particle size of the cerium oxide powder was 5 μm, it was determined that measuring PM10 concentrations would capture the particle range of the cerium oxide particles. A mass balance was also performed and the amount of soil and simulant lost during the experiment

was calculated. Additional information on simulant preparation and application is presented in Section 4.3.

3.2 Experimental setup

3.2.1 Soil penetration depth experiments

The candidate fixatives were tested to determine the maximum depth of penetration. The parameters varied included the concentration of fixative and the soil moisture content. These tests helped determine what quantity of fixative is required for varying soil conditions to achieve a certain penetration depth. In order to complete these tests, an experimental setup was developed. The setup consisted of four (4) acrylic columns with a 2.5" internal diameter (I.D.) and a 24" length. Each column was sealed at the bottom with a machined piece of acrylic sheet and was supported by a wood and uni-strut frame to keep the column from moving during soil placement and fixative pouring. A measuring strip was attached to each column during the various test cycles to maintain a visual record of the penetration depth (Figure 2).

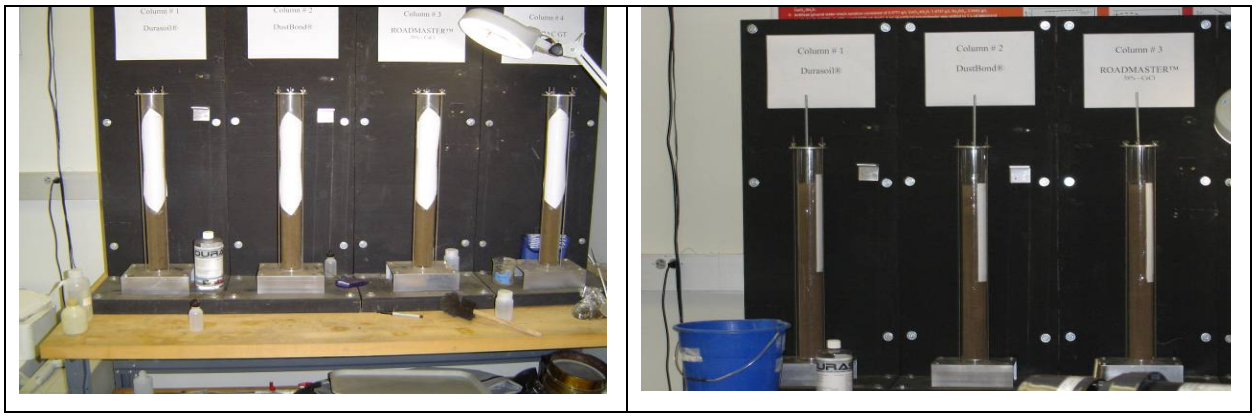

Figure 2 Experimental setup for penetration depth studies

The initial experimental procedure used a fluorescent powder mixed with the fixative to monitor penetration depth. After several trial tests, it was determined that the fluorescent powder was not needed; the penetration depth could be assessed more accurately via visual measurement. The fixatives, using manufacturer recommendations, were poured into the soil columns containing different soil moisture contents and allowed to penetrate for 2 hours. After the drying/curing period, a visual depth-of-penetration measurement was taken against a measuring strip adhered to the column (Figure 2). In order to address the random structure

of the soil after being placed in the column, the tests were repeated three times for each fixative and soil moisture element.

The soil was first sieved using an ASTM No. 12 sieve to remove larger debris (roots, weeds, large rocks); this would minimize potential deviations caused by debris improving or degrading penetration depths. The soil was then examined three times for initial soil moisture content by weight using an OHAUS MB200 moisture analyzer. Based on the analysis results, the soil was either allowed to dry or additional water was added to achieve the designated moisture content. The soil was then mixed manually and the moisture level was again checked three times to ensure that it had reached the needed percentage. Once the moisture content result was verified, the soil was placed into the columns via a scooper and a funnel. The amount of soil for each column was 1 – 1.5 liters per test and was varied depending on previous penetration depth and soil moisture content. The test matrix called for testing at 5%, 10%, 15% and 25% soil moisture change but after several trial runs, it was determined that testing at lower concentrations would be more beneficial, as Hanford soil showed soil moistures less than 2.7% by weight. The modified test matrix consisted of 1.2%, 2.7%, 3.7%, 5.3%, and 7.7% soil moisture change. Additional tests were performed at higher soil moistures for fixatives that showed improvements with increasing soil moisture.

Each manufacturer provided application rates (Table 4) for various footprints and penetration depths. These application rates were adjusted for the column footprint and poured using pipettes or plastic application bottles.

Table 4 Vendor recommended fixative application rates

Name	Application Rate (gal/sq. yd.)	Unit Conversion (ml/sq. in.)	Volume Used per Column (ml)
DuraSoil® (6"penetration depth)	1.80	5.26	25.81
DustBond®	1.5 (7:1)	4.38	21.51
RoadMaster™	0.4	1.17	5.74
TACPAC-GT	40 lb/acre mixed in 1000 gallons of water	6.37×10^{-6} lb/sq. in.	2.36

Once the fixative was poured on the surface (Figure 3), it was allowed to penetrate through the soil for 2 hours. After the 2 hour period, a measurement of the penetration depth was taken, marked on the removable measuring strip and logged in the lab notebook (with a time tag). Of the three tests performed per soil moisture content, one was allowed to continue to determine a 20 hour penetration depth and for comparison to the 2 hour test. The depth measurement process involved examining the column using room lighting and then using a flashlight on top of the column. Due to the semi-transparent nature of the fixatives, the flashlight was useful in determining where the reflectivity of the column changed, which was associated with where the fixative had ceased to penetrate. This measurement method was later verified during column clean-up by examining where the "chunks" of fixative/soil debris ceased. After the soil was removed from the column, the column surface was cleaned with a brush.

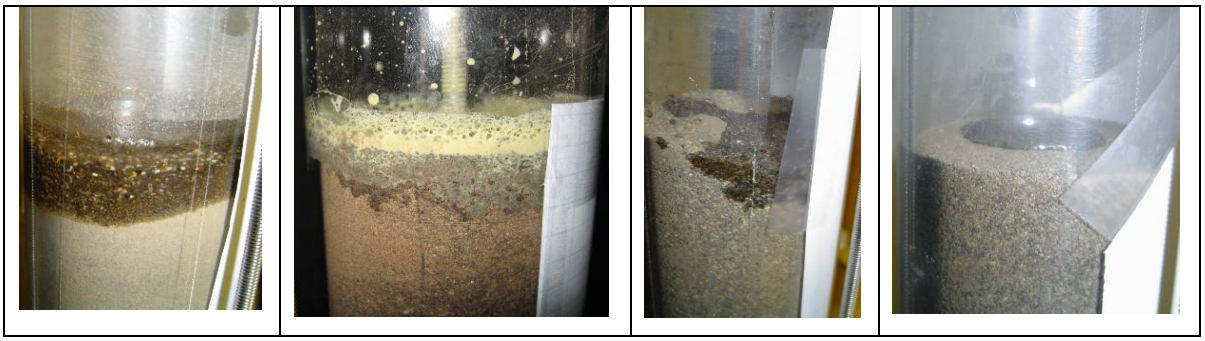

Figure 3 Pouring of fixatives on soil column surface. From left to right: Durasoil®, Dustbond®, Roadmaster™, and TACPAC GT

The mean penetration depths were calculated using the AVERAGE () function and deviations using the STDEV () function. The values were then plotted using a line graph. The moisture values used for each measurement cycle are provided in the results section.

3.2.2 Wind force experiments

Wind force experiments were conducted in an open-loop, low-speed wind tunnel [Engineering Lab Design (ELD), Model #304]. The wind tunnel had a 1 ft x 1 ft x 2 ft test section with overall dimensions of 19.2 ft x 6.3 ft x 6.3 ft (Figures 4 and 5). This wind tunnel allowed the samples to be exposed to a sustained wind speeds ranging from 10 to 30 mph. The wind tunnel test section was modified to allow room for placing soil samples with overall dimensions of 3 in. x 3 in. x 1 in. The wind tunnel test section had a cross-sectional area of

12 in. x 12 in. The test section of the wind tunnel was equipped with a Pitot tube for dynamic pressure measurements. Velocity measurements were recorded in the middle of the soil samples at 5 vertical distances from the surface of the soil sample (0.25”, 3”, 6”, 8“, and 10”). A Phantom V5.1 high-speed camera was installed next to the test section to provide flow visualization. This flow visualization technique provided evidence of the soil movement (creeping and saltation). An aerosol analyzer instrument (TSI 8520 Dust Track) was placed in the test section immediately downstream from the soil sample tray so that airborne soil particles could be measured. In addition, downstream from the wind tunnel test section, a collection box was installed to collect and measure soil displaced by the wind force. The soil samples used during these experiments were shaped in the form of a mound.

Figure 4 Open loop low-speed wind tunnel

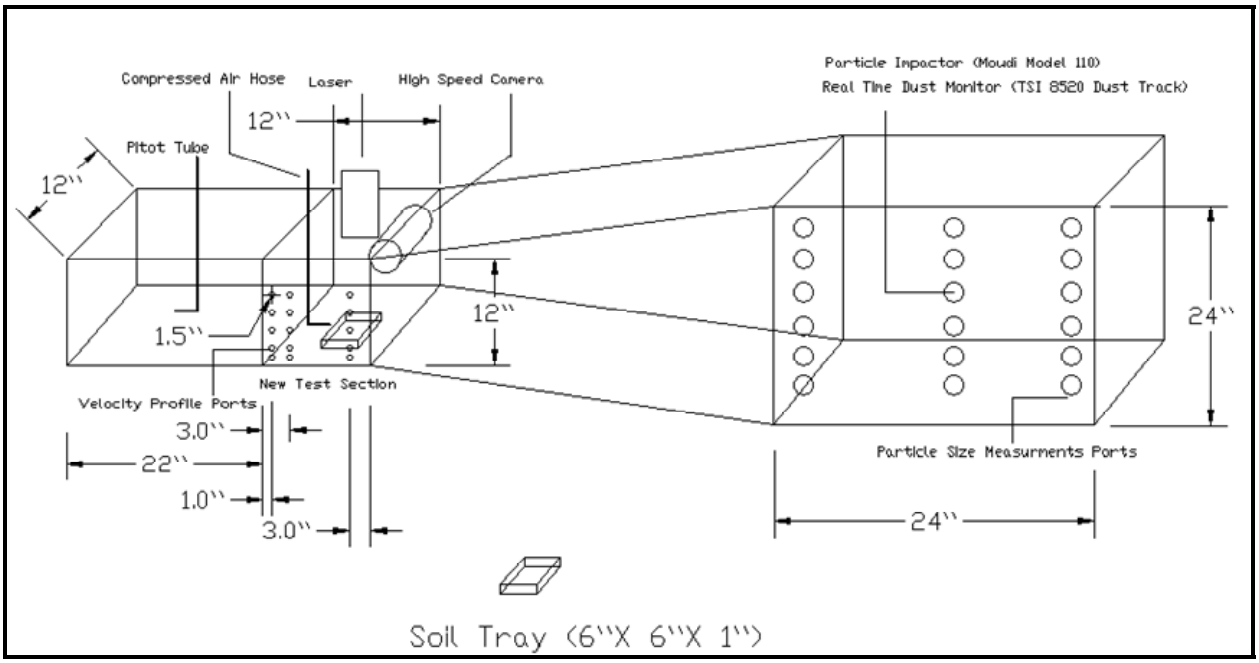

Figure 5 Experimental setup of wind tunnel experiments

4.0 SAMPLE PREPARATION AND APPLICATION

4.1 Hanford's SP soil with varying soil moisture by weight (2.7%, 5%, 10%, 15%, and 20%)

Each soil sample was prepared with specific moisture content by weight. The moisture content of the soil samples used during the study were 2.7%, 5%, 10%, 15%, and 20% by weight. Soil samples with specific moisture contents were prepared using Hanford's SP sandy soil (see Section 3.1.3), having a baseline moisture content of 2.7%, and 224 grams of wet soil. Since the density of water is 1 g/ml, the amount of water added to 218 grams of soil with 2.7% moisture to attain 224 grams of soil with 5.0% moisture was 5.15 ml. (see Table 5 for detailed calculations). Table 6 summarizes the amount of water added to the soil sample to obtain a moisture variation between 5% and 20%. Moisture content of the samples was measured by following the same procedures described in Section 3.1.3; the amount of moisture in the Hanford soil samples was measured and verified for each sample used during these experiments. The samples were prepared and immediately placed in the test section of the wind tunnel. The change in moisture in the soil sample was also measured and recorded after each velocity regime.

Table 5 Calculations for obtaining samples with 5% moisture

Calculations	Calculation Results
Weight of the wet sample required	224 grams
Desired final moisture	5.0 % by weight
Mass of water present in 5.0% moisture soil	0.05 * 224 = 11.2 grams
Mass of dry soil (0.0% moisture)	0.95 * 224 = 212.8 grams
Moisture of the baseline soil	2.7 % by weight
Mass of the water present in 2.7% moisture soil	0.027 * 224 = 6.05 grams
Mass of 2.7% moisture soil required	212.8 + 6.05 = 218.85 grams
Mass of water to be added	11.2 – 6.05 =5.15 grams (ml)

Table 6 Amount of soil and water for developing desired Hanford soil samples with varying percent moistures

Moisture %	Amount of 2.7% moisture soil used (grams)	Amount of water added (ml)
5.0	218.85	5.15
10.0	207.65	16.35
15.0	196.45	27.55
20.0	185.25	38.75

4.2 Fixatives Selected and used in wind tunnel experiment

4.2.1 RoadMaster™ (calcium chloride)

The RoadMaster™ fixative is commonly shipped as a 38% calcium chloride ($CaCl_2$) concentration and has a manufacturer's recommended application rate of 0.4 gal/sq. yd. Preliminary wind tunnel experiments were conducted at this concentration and application rate but no soil movement was detected/observed. Based on this fact, new RoadMaster™ dilution rates of 2.5%, 5%, 7.5% and 10.0% and application rates were calculated and used for these experiments. Also, based on the sample size (3 in x 3 in x 1 in) used in these experiments, a new application volume was calculated (Table 7). This was done in an effort to identify the application rate at which soil movement does occur.

Table 7 RoadMaster™ application rate calculations

Calculations	Calculation Results
Manufacturer's recommended application rate	0.4 gal/sq. yd. = 1.17 ml/sq. in.
Application area	3" x 3" = 9 sq. in.
Volume RoadMaster™ applied on each sample	9 * 1.17 = 10.53 ml

Since the RoadMaster™ has a calcium chloride concentration of 38%, 9.84ml, 9.15ml, 8.46ml and 7.77ml of water was added to attain dilutions of 2.5%, 5.0%, 7.5% and 10.0%, respectively to obtain a total application volume of 10.5 ml of RoadMaster™. Equation 2.0 was used to obtain the above values:

$$C_1 V_1 = C_2 V_2 \qquad \text{Equation 2.0}$$

Where:

C_1 = Initial concentration of the solution
V_1 = Initial volume of the solution
C_2 = Final concentration of the solution
V_2 = Final volume of the solution

Since the final volume of the solution (V_2) is 10.53 ml and the initial concentration (C_1) is 38% calcium chloride (as shipped), calculating the amount of 38% calcium chloride and the amount of water needed to dilute the calcium chloride to a 2.5% solution was achieved by solving Equation 2.0 in terms of V_1:

$$\begin{aligned} V_1 &= \frac{C_2 * V_2}{C_1} \\ &= \frac{2.5 * 10.53}{38} \\ &= 0.69\ ml \end{aligned} \qquad \text{Equation 3.0}$$

The amount of water required to dilute a 38% calcium chloride solution to a 2.5% calcium chloride solution is equal to 9.84 ml (10.53 ml – 0.69 ml = 9.84 ml)

Table 8 shows the new calculated dilution ratios for the calcium chloride fixative.

Table 8 Dilution rate calculations for RoadMaster™

Dilution (%)	Volume of 38% Calcium Chloride required (ml)	Amount of water to be added (ml)
2.5	0.69	9.84
5.0	1.38	9.15
7.5	2.07	8.46
10	2.76	7.77

Once the required dilution ratios and application rates were obtained, the derived amount of RoadMaster™ was sprayed onto approximately 224 grams of Hanford's SP soil containing an initial moisture content of 2.7%. Figure 6 shows a representative soil samples after applying RoadMaster™ fixative at 10% $CaCl_2$. The fixative application was accomplished by spraying the solutions onto the soil sample. It can be seen from Figure 6 that the RoadMaster™ covered 100% of the surface of the soil sample.

Figure 6 RoadMaster™ (230 grams at 10% $CaCl_2$)

4.2.2 DustBond®

Initial wind tunnel experiments were conducted using the manufacturer's recommended application rate of 1.5 gal/sq. yd. (4.38 ml/sq. in.) and a recommended dilution ratio of 7.0: 1.0 (Water : Dustbond®). This application rate did not allow for any visible movement in the soil during initial wind tunnel experiments, so new dilution ratios and application rates were calculated. This was done in an effort to identify the application rate at which soil movement does occur. These calculations and new application rate values are presented in Tables 9 and 10.

Table 9 DustBond® dilution ratio calculations

Calculations	Calculation Results
Recommended application rate	1.5 gal/sq. yd. = 4.38 ml/sq. in.
Application area	3" x 3" = 9 sq. in.
Volume DustBond® and water mixture applied on each sample	9 * 4.38 = 39.42 ml
Recommended dilution ratio	7.0 : 1.0 (Water : DustBond®)
Amount of DustBond® required	39.42 * 1/8 = 4.93 ml
Amount of water required	39.42 * 7/8 = 34.49 ml

Since the amount of water added to obtain the recommended application rate is very high (34.49 ml) and would increase the moisture of the soil to over 20%, it was decided to reduce the dilution ratio, thus reducing the application rates for subsequent experiments. In addition to the 7.0:1.0 (Water : DustBond®), two new dilution ratios of 1.0:1.0, 0.5:1.0 (Water : DustBond®) were calculated and used for these experiments. For these experiments, the amount of DustBond® required was kept constant but the amount of water added to the soil sample was reduced. Based on these dilution ratios, new application rates were determined.

Table 10 below shows the calculated effective application rates applied for each sample.

Table 10 DustBond® dilution ratios and application rates calculations

Dilution Ratio (water : Dustbond®)	Amount of water (ml)	Amount of DustBond® (ml)	Total Volume applied (ml)	Effective application rate (gal/sq. yd.)
7.0 : 1.0	34.49	4.93	39.42	1.500
1.0 : 1.0	4.93	4.93	9.86	0.375
0.5 : 1.0	2.465	4.93	7.395	0.280

Once the application rates were obtained, the derived amount of DustBond® was sprayed onto 224 grams of Hanford's SP soil containing an initial moisture content of 2.7%. Figure 7 shows one of the samples after applying the DustBond® fixative at a dilution ratio of 7.0:1.0 (Water : DustBond®). It can be seen that the DustBond® covered 100% of the surface of the soil sample for a dilution ratio of 7.0:1.0 (Water : DustBond®). This was also the case for the other two dilution ratios of 1.0:1.0 and 0.5:1 (Water : DustBond®).

Figure 7 DustBond® applied to soil at dilution ratio of 7.0:1.0 (Water : DustBond®)

4.2.3 DuraSoil®

As an initial step, DuraSoil®, at 100% strength of the manufacturer's recommended application rate of 0.45 gal/sq. yd. (1.31 ml/sq. in.), was mixed with soil. After preliminary wind tunnel experiments, it was observed that there was very little soil movement (1 gram) at manufacturer's recommended application rate. Due to the insignificant amount of soil movement, two additional application rates were prepared and used in subsequent experiments (25% and 50% of the manufacturer's recommended application rate (0.45 gal/sq. yd)). This was done to identify the application rate at which soil movement does occur. Application rates were prepared based on the following calculations (Table 11).

Table 11 DuraSoil® application rates used during experiments

Calculations	Calculation Results
100% of recommended application rate (100%)	0.45 gal/sq. yd. = 1.31 ml/sq. in.
Application area	3” x 3” = 9 sq. in.
Volume DuraSoil® applied on each sample	9 * 1.31 = 11.8 ml
50% of recommended application rate	0.45 gal/sq. yd. *0.50 = 0.66 ml/sq. in.
Application area	3” x 3” = 9 sq. in.
Volume DuraSoil® and water mixture applied on each sample	9 * 0.66 = 5.94 ml
25% of recommended application rate	0.45 gal/sq. yd. * 0.25 =0.1125 gal/sq. yd.=0.33 ml/sq. in.
Application area	3” x 3” = 9 sq. in.
Volume DuraSoil® applied on each sample	9 * 0.33 = 2.97 ml

It was also discovered that the DuraSoil® fixative was not readily sprayable so the application of this fixative was accomplished by pouring the fixative using dropper. The derived amount of DuraSoil® was poured onto 224 grams of Hanford’s SP soil containing an initial moisture content of 2.7%. It can be seen from Figure 8 that the DuraSoil® covered only approximately 80% of the surface of the soil sample.

Figure 8 DuraSoil® applied to soil at 100% application rate

4.3 Cerium oxide simulant

A plutonium powder simulant (cerium IV oxide) was selected, mixed with Hanford's SP soil and fixatives, and used in wind tunnel experiments. Four distinctive cerium oxide concentrations were used during these experiments. The concentrations used were 5%, 10%, 15%, and 20%. The selected simulant is a very fine powder whose transportation characteristics were observed during the wind tunnel experiments. Airborne particulate data was recorded to quantify the amount PM10 particulates generated by the presence of the cerium oxide simulant. A mass balance was also performed and the amount of soil and simulant lost during the experiments was calculated. Table 12 details the calculation for cerium oxide concentrations of 5%.

Table 12 Cerium oxide calculation for preparing 5% concentration

Calculations	Calculation Results
Weight of the soil sample required	224 grams
Desired cerium oxide %	5.0 % by weight
Weight of cerium oxide required	0.05 * 224 = 11.2 grams
Total mass (soil plus % of cerium oxide)	11.2 grams + 224 grams = 235.2 grams

Table 13 shows the preparation of Hanford's SP soil with varying percent moisture (2.7%, 5%, and 20%) mixed with cerium oxide. The final sample weight is the summation of the amount of cerium oxide and the 224 grams of soil. For example, in the case of 5% moisture, the amount of 5.15 ml (5.15 grams) of water was added to 218.85 grams of soil to add up to the required 224 grams of soil, and then 5% cerium oxide (11.2 grams) was added to the 224 grams of soil resulting in a final sample weight of approximately 235 grams.

Table 14 shows the preparation of the soil, fixative, and cerium oxide mixture. As a first step, the cerium oxide was added to Hanford's SP soil to add up to the required 224 grams, and then the fixatives were sprayed and/or poured to the soil/cerium oxide mixture. For example, in the case of RoadMaster™ with a dilution ratio of 2.5% and a cerium oxide concentration of 5%, 11.2 grams of cerium oxide was added to 212.8 grams of soil giving a total of 224 grams of soil and cerium oxide; then a total amount of 10.53 ml (0.69 ml of RoadMaster™ and 9.84

ml of water) of RoadMaster™ fixative was sprayed onto the soil/cerium oxide mixture giving a total sample weight of 234.5 grams.

Table 13 Soil moisture of 2.7%, 5% and 20% mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

			Amount of cerium oxide (grams)			
Soil Moisture %	**Amount of soil used (grams)**	**Amount of water added (ml)**	**5%**	**10%**	**15%**	**20%**
2.7	224.00	-	11.2	22.4	33.6	44.8
5	218.85	5.15	11.2	22.4	33.6	44.8
20	185.25	38.75	11.2	22.4	33.6	44.8

Table 14 Fixative and cerium oxide concentration calculations

Fixative	**Dilution**	**Volume of fixative required (ml)**	**Amount of water to be added (ml)**	**Amount of cerium oxide + soil (grams)**				**Amount of sample (grams)**
				5%	**10%**	**15%**	**20%**	
Road Master™	**2.50%**	0.69	9.84	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	234.5
	10%	2.76	7.77	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	234.5
DustBond®	**7.0:1.0**	34.49	4.93	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	263.4
	0.5:1.0	2.46	4.93	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	231.4
DuraSoil®	**25% AR**	2.97	0	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	227.0
	100% AR	11.88	0	11.2 + 212.8	22.4 + 201.6	33.6 + 190.4	44.8 + 179.2	235.9

5.0 RESULTS AND DISCUSSION

5.1 Results of the penetration depth studies

Based on the described experimental approach (see Section 3.2), Figure 9 below shows the results obtained for soil penetration depth of the candidate fixatives. Roadmaster™ and TACPAC GT fixatives showed mild fluctuations for varying soil moisture content, and penetration depth was mostly constant regardless of moisture. Two fixatives, namely Durasoil® and Dustbond®, showed large variations based on changing soil moisture content. Due to the responses of these two last fixatives, additional soil moisture contents were tested to determine the results.

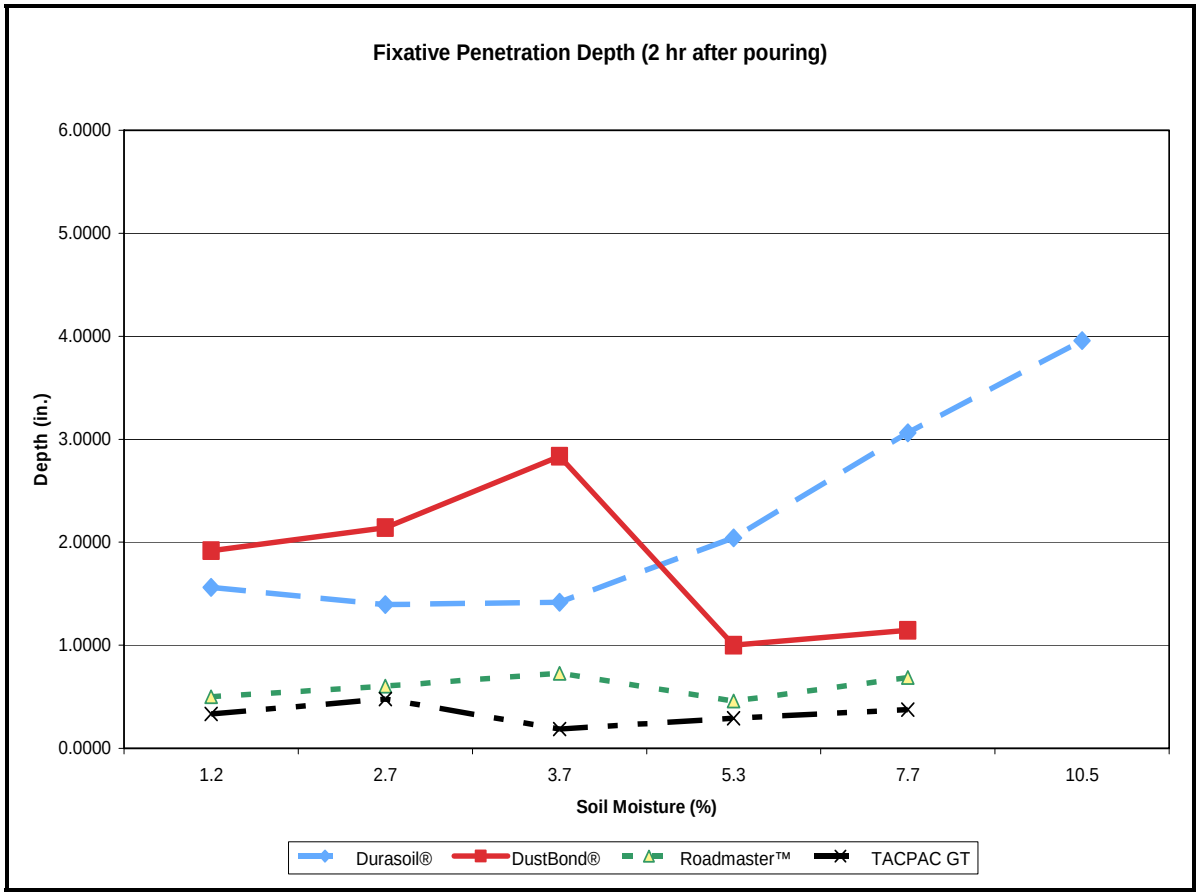

Figure 9 Penetration depth results after 2 hours of application

As shown in Figure 9, the calcium chloride fixative (RoadMaster™) showed mild fluctuations with varying soil moisture contents. After 2 hours of penetration, the fixative was found to

have agglomerated the particles into one solid mass, although easy to break (Figure 10). The quantity used for this fixative was very low (5.74 ml), which could indicate why there was minimal penetration depth. The TACPAC GT (2.36 ml) showed very little penetration depth with varying soil moisture and this was consistent with what was expected of a liquid with slime-like consistency. It also was very effective in creating a hardened shell (crust) on the surface of the soil (Figure 10) although the application rate made it the lowest volume applied to the soil (with the recommended application rate it was able to cover only part of the top surface). One quick test trial in increasing the application rate of the TACPAC GT to something equivalent to the other fixatives (10 times the recommend rate, or 23.6 ml) showed no change in penetration depth and only left a large amount of the liquid sitting on top of the soil.

Figure 10 Fixative soil matrix after pouring. Left picture shows resulting matrix from RoadMaster™ fixative; right picture shows resulting TACPAC GT matrix.

The DuraSoil® fixative showed a significant increase in penetration depth with increasing soil moisture content. Using the recommended application rate for a 6" penetration depth, the fixative showed a possibility of achieving such a penetration depth at moisture levels higher than 10%. The main issue with the DuraSoil® was that it required the largest amount of fixative per surface area. Application rates were discussed in the first section and the volume of DuraSoil® used for a 2-inch diameter surface was 25.8 ml, which was large compared to other fixative volumes. The DustBond® fixative showed fluctuations with increasing soil moisture. The DustBond® fixative seemed to increase penetration depth with increasing soil moisture but after approximately 5.3% soil moisture, it decreased penetration depth

substantially. When tested at higher soil moisture content, specifically 7.7%, the fixative seemed to increase again in penetration depth. In order to verify that human error would not account for the fluctuation at 5.3%, three tests were repeated at the same moisture content, only to find that the same lower penetration depth was achieved (see Conclusions Section 6.0).

One test per moisture content was left for 20 hours to determine if there was any improvement with increased setting time. The results for the 20-hr test are shown in Figure 11. Most fixatives showed an increase in penetration depth from 2 to 20 hours. The TACPAC GT fixative did not show any significant variations from the 2 hour test other than more hardening of the crust it creates. The RoadMaster™ showed a larger fluctuation in penetration depth along the moisture contents tested. The DuraSoil® showed the same pattern as in the 2-hr test, with a large increase in penetration depth with increasing soil moisture content. The DustBond® also followed the same pattern as in the 2-hr test, showing a very large dip in penetration depth at the 5.3% soil moisture content. For the repeated tests at 5.3%, the 20-hr test showed the same results for all three tests as seen during the 2-hr test.

The DustBond® and RoadMaster™ showed a similar pattern, with a decrease occurring around the 5.3% soil moisture content. The only possible connection between these two fixatives is that the chemical make-up for DustBond®, 60% petroleum resin, could contain a compound that contains calcium chloride, which explains the similar pattern.

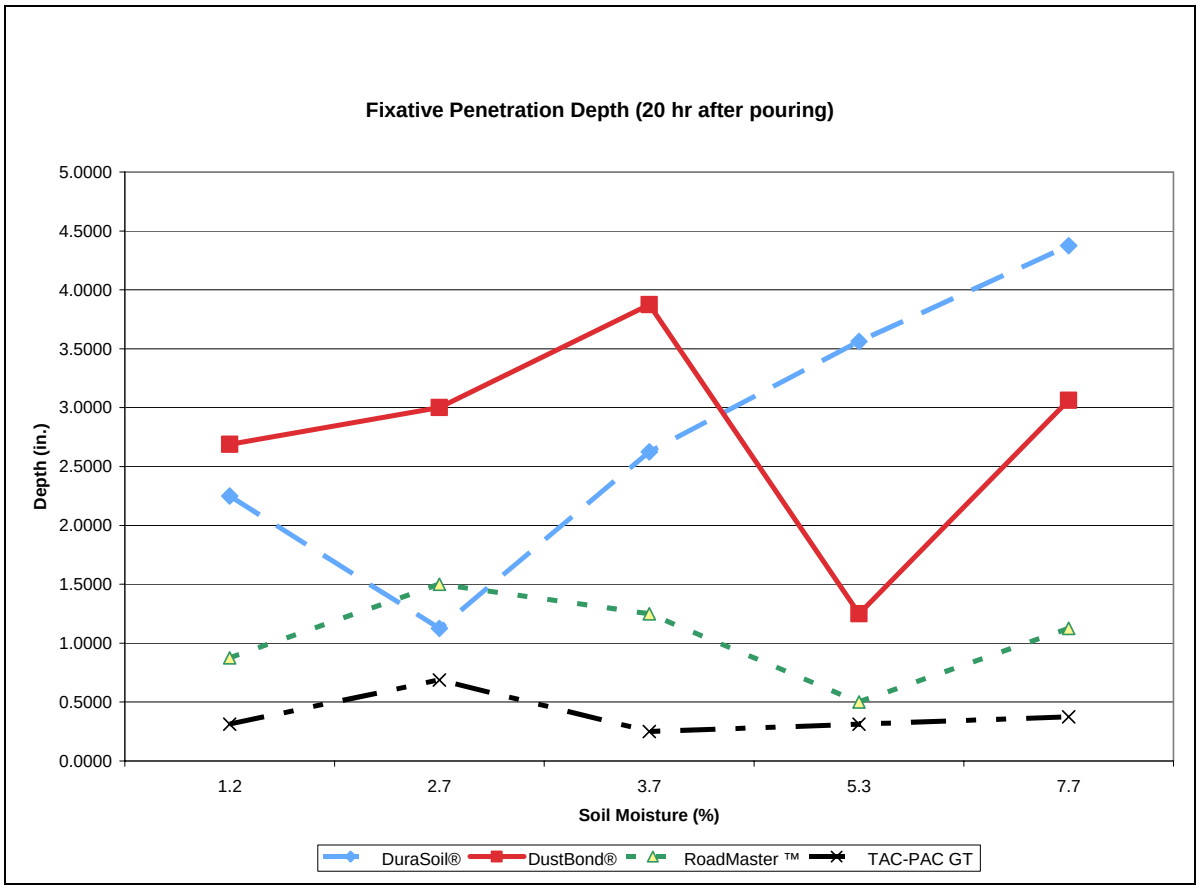

Figure 11 Penetration depth results, after 20 hours of application

5.2 Wind tunnel experimental results

Six different soil matrices were prepared and used for the wind tunnel experiments. These matrices were:

1. Hanford's SP soil with varying soil moisture by weight (2.7%, 5%, 10%, 15%, and 20%).
2. Hanford's SP soil sprayed with various dilution ratios and/or application rates of RoadMaster™ ($CaCl_2$), DustBond® and DuraSoil® fixatives.
3. Hanford's SP soil with 2.7%, 5% and 20% soil moisture by weight mixed with four different concentrations of cerium oxide (5%, 10%, 15% and 20% by weight).
4. Hanford's SP soil at 2.7% moisture sprayed with two different RoadMaster™ ($CaCl_2$) dilution ratios (5% and 10%) and mixed with 5%, 10%, 15% and 20% concentrations of cerium oxide.

5. Hanford's SP soil at 2.7% moisture sprayed with two different dilution ratios of DustBond® (0.5:1 and 7.0:1.0) and mixed with 5%, 10%, 15% and 20% concentrations of cerium oxide.
6. Hanford's SP soil at 2.7% moisture mixed (poured) with two different application rates of DuraSoil® (25% AR and 100% AR) and mixed with 5%, 10%, 15% and 20% concentrations of cerium oxide.

5.2.1 Hanford's SP soil with 2.7% moisture by weight and percent moisture measurements

Hanford's SP soil used for these experiments contained 2.7% moisture by weight (see Section 4.1). The soil was placed in the test section of an open loop, low-speed wind tunnel and exposed to free stream wind speeds varying from 10 to 25 mph. The soil was exposed to each velocity regime for a total of 10 minutes. Duplicate experiments were conducted for data accuracy and consistency. Each sample had an initial average mass of 224 grams soil and a mass balance was conducted by following Equation 1.0. Mass and moisture measurements were conducted at the end of each velocity regime and are presented below. As indicated above, the moisture loss was quantified by measuring the moisture in the soil before and after each velocity regime. Table 15 shows the moisture lost during the wind tunnel experiments for Hanford's SP soil with an initial moisture content of 2.7%. Table 15 represents the average initial and final percent moisture obtained from the set of experiments conducted.

Table 15 Moisture lost during experiment

	2.7% Soil Moisture	
Speed (mph)	**Initial Moisture**	**Final Moisture**
0	2.7%	…
10	2.7%	2.5%
15	2.5%	2.3%
20	2.3%	2.0%
25	2.0%	1.9%

Table 16 represents the average soil displaced for each velocity for the first and second experiments; the data is also visually presented in Figure 12. For soil with an initial 2.7% moisture content, a total average of 164.5 grams (73% of the soil) was collected downstream of the wind tunnel test section for the range of velocities tested. The final average mass remaining in the wind tunnel test section at the end of the experiments was 32.0 grams (14% of the soil). The soil moisture at the end of the experiment was measured to be 1.9% by weight (Table 15). The amount of soil lost due to moisture was calculated to be 1.8 grams (0.8% of the soil). Throughout the experiment, a total of 11.4 grams (5.0% of the soil) was removed from the soil sample and used for moisture measurements. Only 14.3 grams (6.4% of the soil) was lost and unaccounted for. It was concluded that this small amount of soil (6.4%) was airborne and/or escaped through the open back end of the wind tunnel.

Table 16 Average mass displacement for Hanford's SP soil with 2.7% moisture

	2.7% Soil Moisture
Speed (mph)	**Mass at the End of Wind Tunnel (grams)**
10	0.00
15	0.50
20	6.50
25	157.50

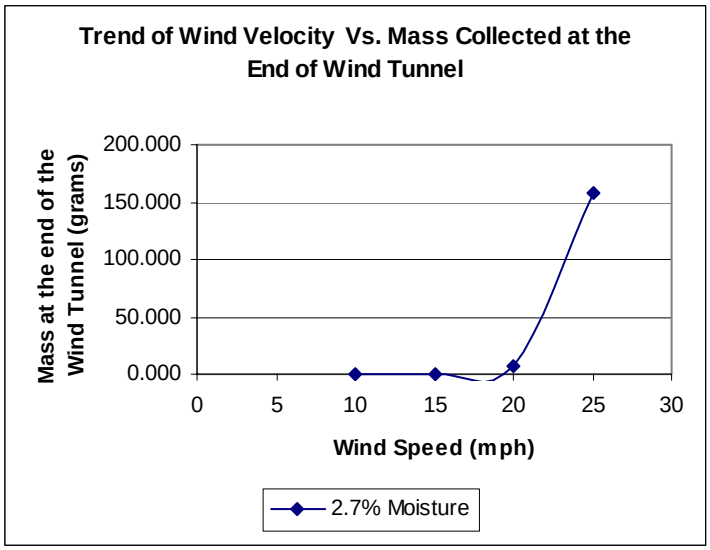

Figure 12 Trend of wind velocity vs. mass collected at end of wind tunnel

Video recording was conducted during these experiments; two video frames are presented in Figure 13 for velocities of 10 mph and 20 mph (left picture represents 10 mph and right picture represents 20 mph). It can be seen from Figure 13 that there was considerable soil displacement when the velocity was increased from 10 mph to 20 mph.

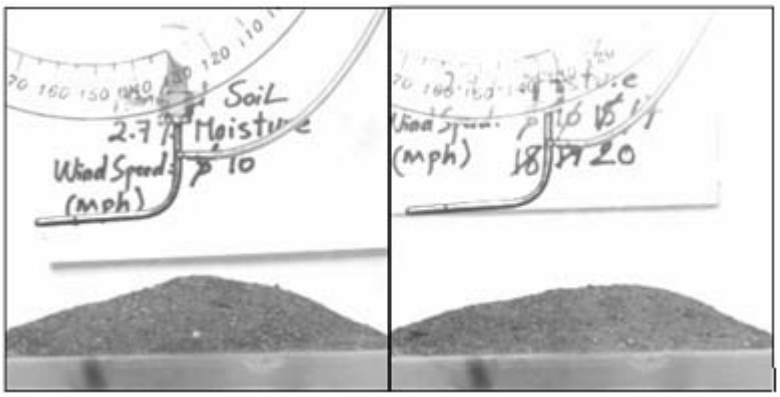

Figure 13 Hanford soil 2.7% moisture at 10 mph and 20 mph

5.2.2 Hanford's SP soil with 5%, 10%, 15% and 20% moisture by weight and moisture measurement

During these experiments, the initial soil moisture in the samples was varied from 5% to 20% by weight (Table 6). For each experiment, the soil was placed in the test section of an open loop, low-speed wind tunnel and exposed to free stream wind speeds varying from 10 to 25 mph. The soil was exposed to each velocity regime for a total of 10 minutes. Duplicate experiments were conducted to assure the repeatability and consistency of the data. Each sample had an initial average mass of 224 grams soil and mass balance was conducted by following Equation 1.0. Moisture measurements and mass balance were conducted at the end of each velocity regime and are presented in Tables 17 and 18, respectively.

The moisture loss was quantified by measuring the moisture content before and after each test for the velocity range tested. Table 17 and Figure 14 show the moisture lost during the wind tunnel experiments for Hanford's SP soil with initial moistures ranging from 5% to 20%. Approximately 40% of the initial moisture was lost due to wind effects. Table 18 and Figures 15 and 16 show the average amount of soil mass collected at the end of the wind tunnel for each velocity regime.

Table 17 Moisture loss due to wind effects

	5% Moisture Soil		10% Moisture Soil		15% Moisture Soil		20% Moisture Soil	
Velocity (mph)	**Initial Moisture**	**Final Moisture**	**Initial Moisture**	**Final Moisture**	**Initial Moisture**	**Final Moisture**	**Initial Moisture**	**Final Moisture**
0	5.0%	…	10.0%	…	15.0%	…	20.0%	…
10	5.0%	4.0%	10.0%	8.0%	15.0%	12.0%	20.0%	18.7%
15	4.0%	3.5%	8.0%	4.5%	12.0%	10.0%	18.7%	16.1%
20	3.5%	3.4%	4.5%	4.4%	10.0%	9.7%	16.1%	15.0%
25	3.4%	2.5%	4.4%	6.0%	9.7%	9.5%	15.0%	13.0%

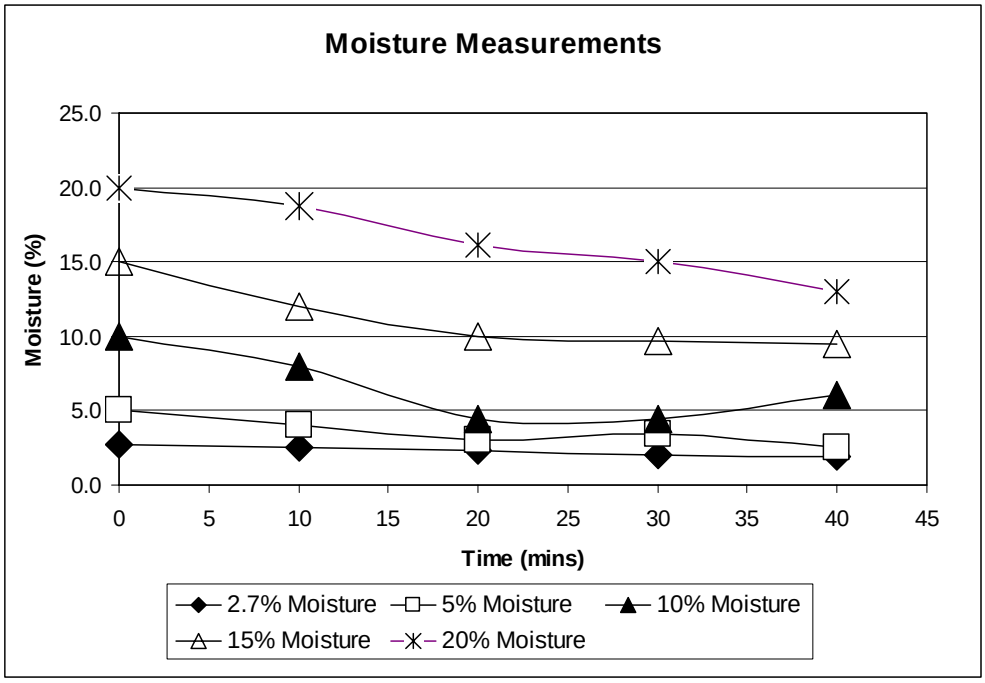

Figure 14 Trend of moisture loss as a function of time

For Hanford's SP soil with an initial **moisture content of 5%**, an initial soil sample of approximately 224 grams was placed in the test section of the wind tunnel. A total average of 117.5 grams (52.4%) of the soil was collected downstream of the wind tunnel's test section. This average was calculated by adding the total mass collected at the back end of the wind tunnel during the experiments. The final average mass of soil, remaining in the wind tunnel test section at the end of the experiments, was 84.0 grams (37.5% of the initial soil). The soil moisture at the end of the experiment was measured to be 2.5% by weight (Table 17). The amount of soil loss due to change in the moisture was calculated to be 5.46 grams (2.4% of the initial soil). Throughout the experiment, a total of 11.9 grams (5.3% of the soil) was collected and used for moisture measurements. Only 5.1 grams (2.3% of soil) was lost

and unaccounted for. It was concluded that part of this small amount of soil was airborne and/or escaped through the open back end of the wind tunnel.

It can be seen from Table 18 and Figure 15 that, for soil with low moisture content such as 2.7% and 5%, a considerable amount of soil was displaced due to increase in the wind velocity. For example at a velocity of 10 mph, there was no soil displacement (0.0 grams) for both soil moistures (2.7% and 5%). When the wind velocity was increased to 25 mph, a much larger amount of soil (157.5 at 2.7% moisture and 111.0 grams at 5% moisture) was lost due to the increasing wind force. Based on the results from these experiments, it was determined that approximately 73% of the soil was displaced when the initial moisture content of the soil was 2.7% and the velocity was increased from 10 to 25 mph. Similarly, over 52% of the Hanford's SP soil was displaced when the initial moisture content of the soil was 5.0% and the velocity profile was increased from 10 to 25 mph. It can also be seen that as the moisture increased, the amount of soil displaced decreased. There was an approximately 20% reduction in total soil loss when the initial moisture content of the sample increased from 2.7% to 5% (i.e. 52.0% of soil was lost at 5% moisture compared to 73.0% of soil lost at 2.7% moisture).

Table 18 Summary of soil mass collected at the end of the wind tunnel

	5% Moisture	**10% Moisture**	**15% Moisture**	**20% Moisture**
Speed (mph)	**(grams)**	**(grams)**	**(grams)**	**(grams)**
10	0.000	0.000	0.000	0.000
15	0.000	0.025	0.000	0.000
20	6.500	0.135	0.030	0.000
25	111.000	1.320	0.230	0.000

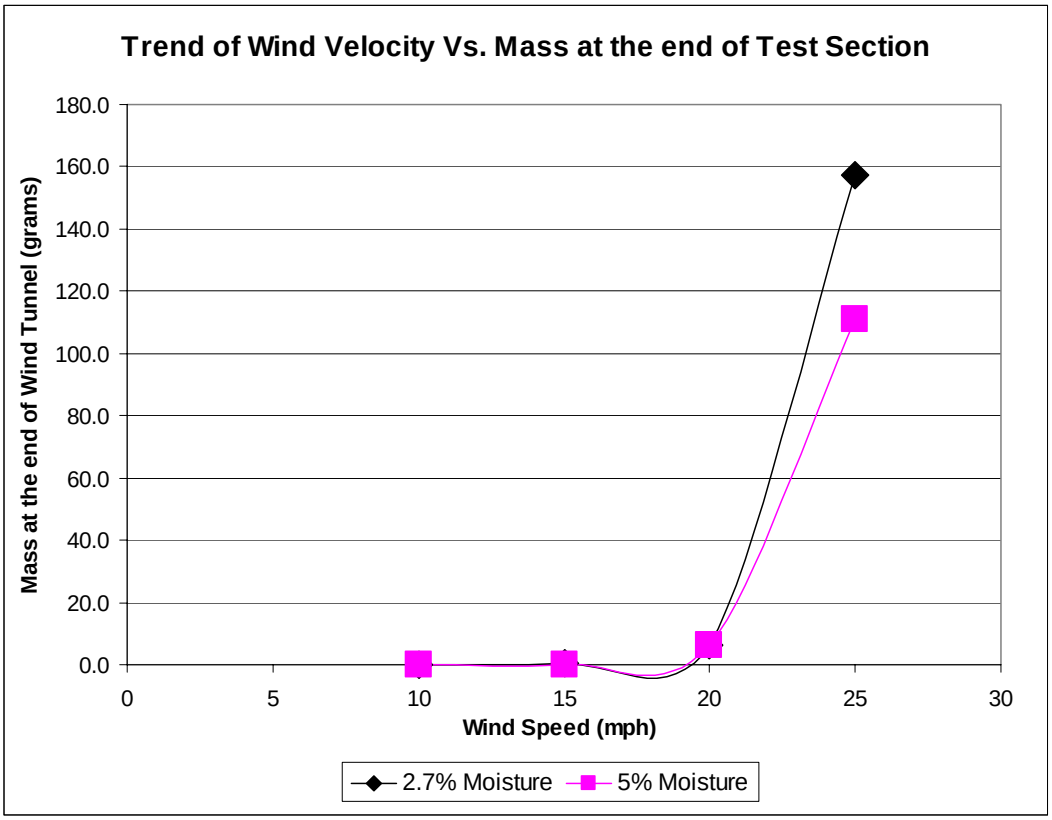

Figure 15 Representation of trend for wind speed vs. mass collected at the end of the wind tunnel

For Hanford's SP soil with an initial **moisture content of 10%**, an initial soil sample of approximately 224 grams was placed in the test section of the wind tunnel. A total average of 1.5 grams (0.7% of the soil) was collected downstream of the wind tunnel test section for the same range of velocities. The final mass average remaining in the wind tunnel test section at the end of the experiments was 201.5 grams (89.9% of the soil). The soil moisture at the end of the experiment was measured to be 6.0% by weight (Table 17). The amount of soil loss due to moisture was calculated to be 8.96 grams (4% of the initial soil). Throughout the experiment, a total of 11.5 grams (5.1% of the soil) was collected and used for moisture measurements. Only 2.04 grams (0.2% of soil) was lost and unaccounted for. Table 17 represents an average of the initial and final moisture content in the soil for the two experiments. It was concluded that part of this small amount of soil was airborne and/or escaped through the open back end of the wind tunnel.

For Hanford's SP soil with an initial **moisture content of 15%**, an initial soil sample of approximately 224 grams was placed in the test section of the wind tunnel. Table 18 and

Figure 16 show that a total average of 0.26 grams (0.1% of the soil) was collected downstream of the wind tunnel test section for the range of velocities. The average final mass of soil remaining in the wind tunnel test section at the end of the experiments was 197.5 grams (88.2% of the soil). The soil moisture at the end of the experiment was measured to be 9.5% by weight. The amount of soil loss due to moisture was calculated to be 12.32 grams (5.5% of the soil). Throughout the experiment, a total of 12.5 grams (5.6% of the soil) was collected and used for moisture measurements. Only 1.68 grams (0.75% of soil) was lost and unaccounted for. It was concluded that this small amount of soil was airborne and/or escaped through the open back end of the wind tunnel.

For Hanford soil with an initial **moisture content of 20%**, an initial soil sample of approximately 224 grams was placed in the test section of the wind tunnel. Table 17 and Figure 16 show that no soil was collected at the back end of the wind tunnel (0.0 grams). The final average mass remaining in the wind tunnel test section at the end of the experiments was 197.0 grams (88.2% of the soil). The soil moisture at the end of the experiment was measured to be 13.0% by weight. The amount of soil lost due to moisture was calculated to be 15.7 grams (7%). Throughout the experiment, a total of 11.3 grams (5.0% of the soil) was collected and used for moisture measurements. Only 0.02 grams (0.008% of soil) was lost and unaccounted for. Table 17 represents the average initial and final percent moisture for the two experiments. It was concluded that part of this small amount of soil was airborne and/or escaped through the open back end of the wind tunnel. Figure 16 shows a graphical representation of the data for soil containing 10%, 15% and 20% moisture by weight.

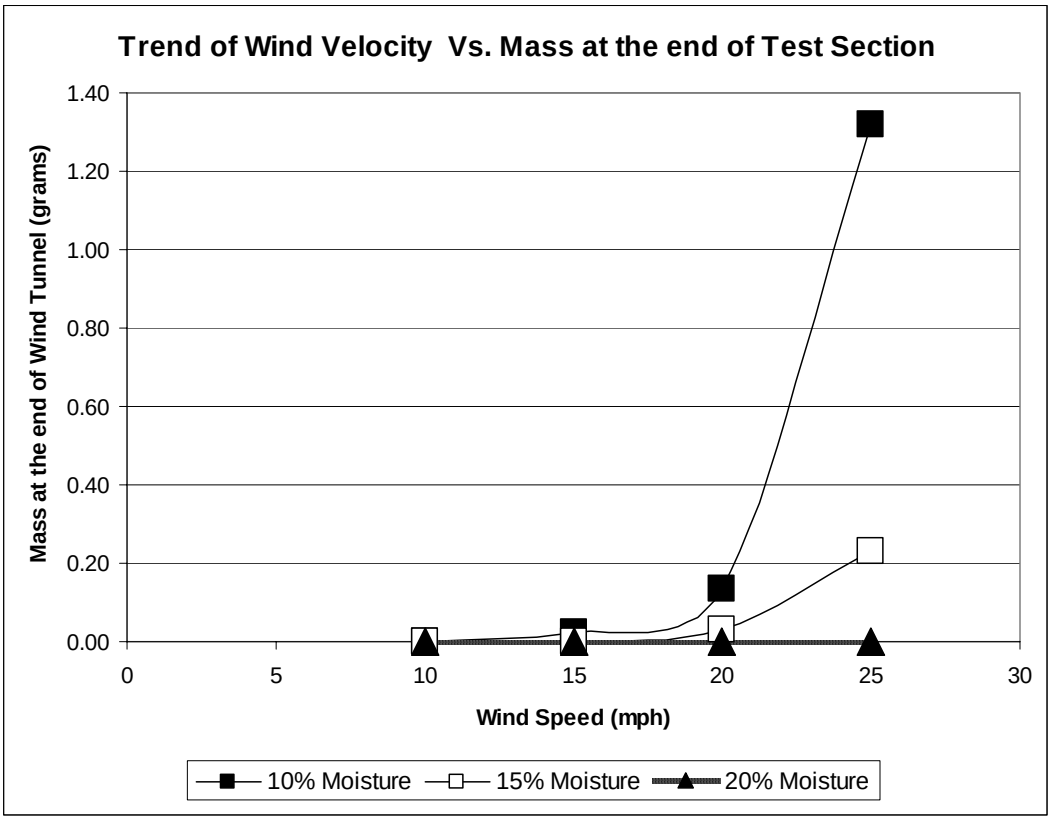

Figure 16 Representation of trend for wind speed vs. mass collected at the end of the wind tunnel for soil moistures of 10%, 15%, and 20%

5.2.3 PM10 concentration experiments for Hanford's SP soil with 2.7%, 5%, 10%, 15% and 20% moisture

PM10 concentrations were measured downstream from the soil mound placed in the wind tunnel test section. A real time dust monitor (TSI 8520 Dust Track) was used to take these measurements. This highly sensitive monitor detects dust and measures PM10, PM2.5 and PM1.0. For the purpose of this research work, PM10 particle size measurements were recorded for an average of 10 minutes per experiment. For the purpose of this study, it was determined that a 10-minute time frame would be sufficient to provide an idea of the amount of airborne particles generated by the wind and the ability of moisture and/or fixatives to suppress PM 10 soil particulates. These measurements are not intended to provide and/or aid in determining Health and Safety (H&S) risk assessments on the fixative tested, or to calculate 8-hour weighted average data for H&S purposes. Simply, the information gathered for this experiment can provide a comparison on the airborne suppression properties of the selected fixatives.

PM10 particle size measurements were collected for Hanford's SP soil with varying percent moisture (2.7% - 20% by weight) for a velocities ranging from 10 to 25 mph. The highest average concentration data is presented in Table 19. PM10 concentrations for 2.7% moisture are represented graphically in Figure 17 and PM10 concentrations for 5% to 20% moisture are presented in Figure 18 for all the velocities tested. The largest concentration recorded for the Hanford soil with 2.7% moisture and at a velocity of 25 mph was 240.225 mg/m^3. The amount of PM10 generated changed with decreasing wind velocity. For example, for the same soil moisture (2.7%) and a wind velocity of 15 mph, the average PM10 concentration decreased to 8.716 mg/m^3. It was also observed that as the soil moisture increased, the PM10 concentration decreased (Table 19). For example, for the same velocity of 15 mph but at 20% moisture, the PM10 concentration was only 0.103 mg/m^3.

Table 19 PM10 concentrations for soil with varying percent moisture

Concentration (mg/m^3)					
Speed (mph)	**Moisture Content**				
	2.7%	**5%**	**10%**	**15%**	**20%**
10	1.582	0.098	0.095	0.092	0.091
15	8.716	0.107	0.105	0.104	0.103
20	233.390	0.385	0.283	0.252	0.142
25	240.225	0.480	0.300	0.269	0.173

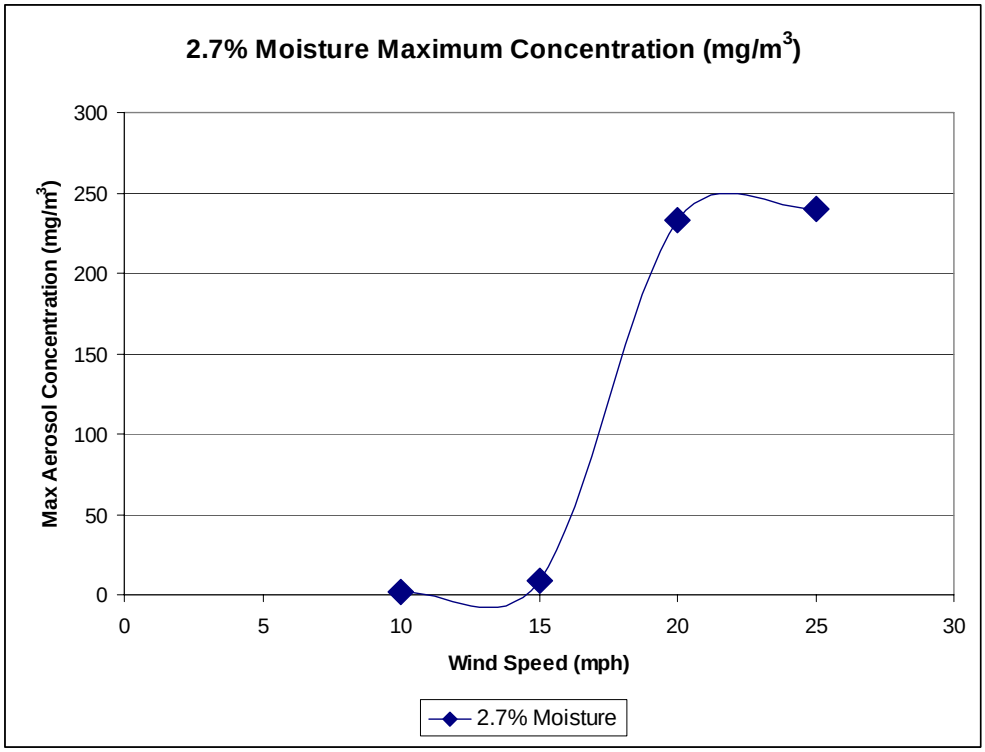

Figure 17 PM10 concentrations– Hanford's SP soil with 2.7% moisture at various wind velocities

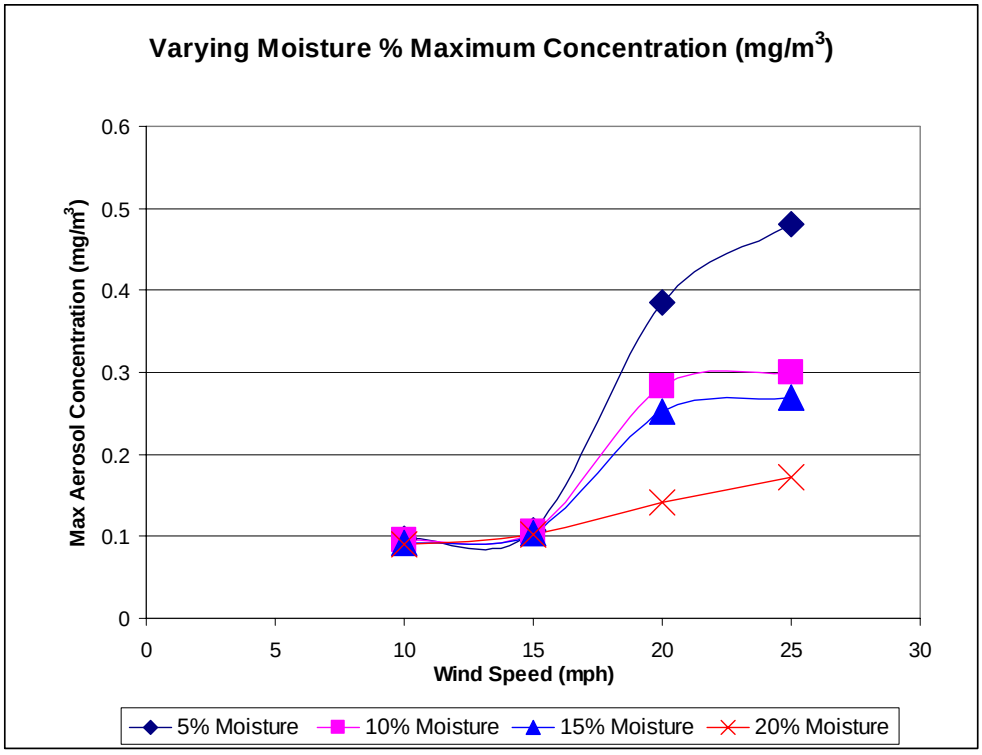

Figure 18 PM10 concentrations – Hanford's SP Soil with varying percent moisture and wind velocities

5.2.4 Hanford's SP soil treated with selected fixatives

Hanford's SP soil with an initial soil moisture content of 2.7% was used for these experiments. Soil samples, with approximate weight of 224 grams, were measured and verified for moisture content (2.7%). The samples were sprayed (RoadMaster™ and DustBond®) or poured (DuraSoil®) with the selected fixatives. The addition of the fixatives increased the overall weight of the soil samples. The velocity range for these experiments varied from 10 to 30 mph. Moisture measurements were not conducted during these experiments so that the fixative film on the soil mound would not be disturbed.

For these wind tunnel experiments three commercially available fixatives were selected and tested. The fixatives included:

- RoadMaster™
- DustBond®
- DuraSoil®

5.2.4.1 RoadMaster™ (calcium chloride) experiments

For a **dilution ratio of 2.5% RoadMaster™**, an initial soil sample of approximately 230 grams was placed in the test section of the wind tunnel (this amount was a bit lower than the pre-calculated value of 234.5 grams). For this experiment, a total average of 10.0 grams (4.3% of the soil) was collected downstream of the wind tunnel test section for this range of velocities. This average was calculated by adding the total mass collected at the back end of the wind tunnel experiments. The final mass average remaining in the wind tunnel test section at the end of the experiments was 210.0 grams (91.3% of the soil). An average of approximately 10 grams (4.3%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For a **dilution ratio of 5% RoadMaster™**, an initial soil sample of approximately 232 grams was placed in the test section of the wind tunnel. For this experiment, a total average of 5.0 grams (2.1% of the soil) was collected downstream of the wind tunnel test section for the same velocities range. This average was calculated by adding the total mass collected at the back end of the wind tunnel experiments. The final mass average remaining in the wind tunnel test section at the end of the experiments was 216.0 grams (93.1% of the soil). An

average of approximately 11 grams (4.7% of the soil) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **dilution ratios of 7.5% and 10% RoadMaster™**, initial soil samples of approximately 231 grams were placed in the test section of the wind tunnel. For this experiments, a total average of 2.0 grams (0.8% of the soil) and 0 grams were collected downstream of the wind tunnel test section for velocities ranging from 10 to 30 mph, respectively. This average is calculated by adding the total mass collected at the back end of the wind tunnel experiments. The final average mass remaining in the wind tunnel test section at the end of the experiments was 222.0 grams (96.1% of the soil) and 220 grams (95.2% of the soil), respectively, for these two concentrations. An average of approximately 7 grams (3.0% of the soil) and 11 grams (4.8% of the soil), respectively, was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

Table 20 and Figure 19 provide an average of the data collected during these experiments.

Table 20 Soil mass collected at the end of the wind tunnel for RoadMaster™

	2.5% RoadMaster™	5.0% RoadMaster™	7.5% RoadMaster™	10% RoadMaster™
Speed (mph)	**(grams)**	**(grams)**	**(grams)**	**(grams)**
10	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00
20	1.00	0.00	0.00	0.00
25	2.00	1.00	0.00	0.00
28	3.00	2.00	1.00	0.00
30	4.00	2.00	1.00	0.00

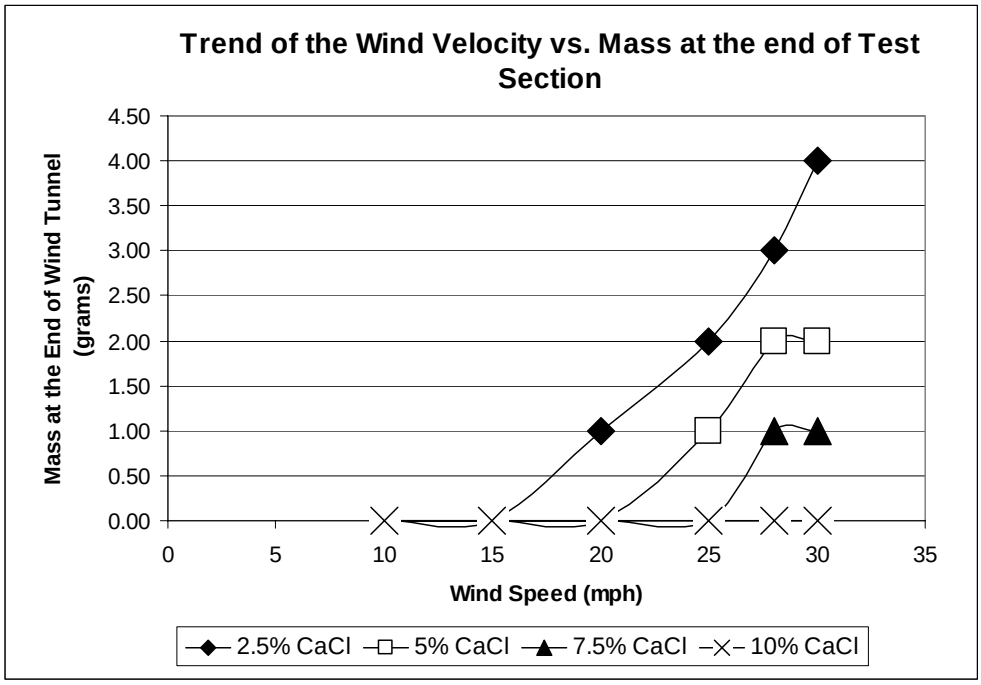

Figure 19 Wind speed vs. mass at end of wind tunnel for RoadMaster™ calcium chloride solution at 2.5%, 5%, 7.5%, and 10% dilution ratios

Based on the results of these experiments, it was determined that the RoadMaster™ provided excellent soil suppression when the soil was exposed to the prescribed velocities. Figures 20 and 21 show a visual representation of the soil movement; it can be observed that little soil movement was detected from 10 to 30 mph. Since no soil movement (0 grams) was detected at a 10% calcium chloride concentration, the manufacture's recommended solution (38% calcium chloride) was not tested.

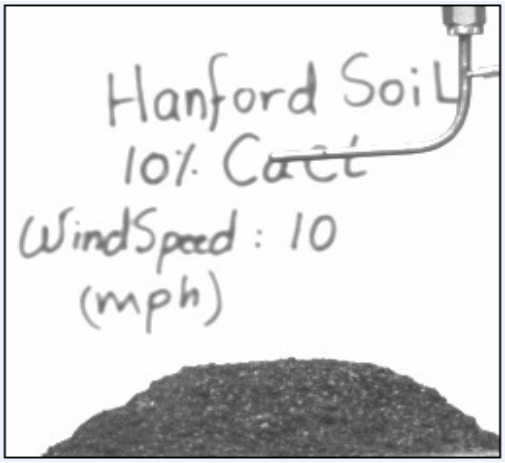

Figure 20 RoadMaster™ 10% at 10 mph

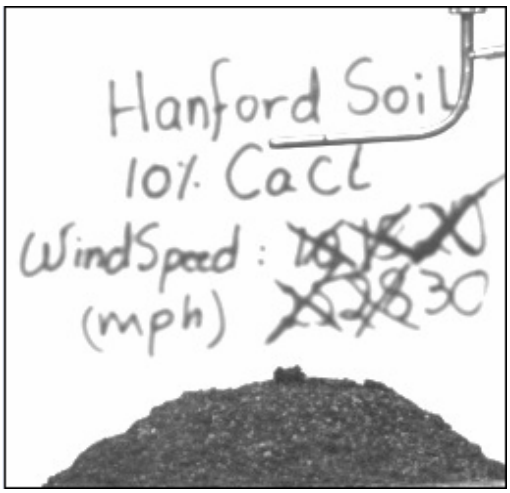

Figure 21 RoadMaster™ 10% at 30 mph

5.2.4.2 DustBond® experiments

For these experiments, dilution ratios and new concentration rates for DustBond® fixative were calculated and used (See Table 10). This was done in an effort to identify the application rate at which soil movement does occur.

For a calculated **dilution ratio of 0.5:1.0** (Water : DustBond®), a soil sample of approximately 231 grams was placed in the test section of the wind tunnel. For this experiment, a total average of 3.0 grams (1.3% of the soil) was collected downstream of the wind tunnel test section for velocities ranging from 10 mph to 30 mph. The final average mass remaining in the wind tunnel test section at the end of the experiments was 223.0 grams (96.5% of the soil). An average of approximately 4.3 grams (1.8% of the soil) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For a calculated **dilution ratio of 1.0:1.0** (Water : DustBond®), a soil sample of approximately 234 grams was placed in the test section of the wind tunnel. For this experiment, a total average of 1.0 grams (0.4% of the soil) was collected downstream of the wind tunnel test section for velocities ranging from 10 mph to 30 mph. The final mass average remaining in the wind tunnel test section at the end of the experiments was 230.0 grams (98.2% of the soil). An average of approximately 3.6 grams (1.6% of the soil) of soil

was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For the manufacturer's recommended **dilution ratio of 7.0:1.0** (Water : DustBond®) an initial soil sample of approximately 242.5 grams (this amount was lower than the calculated value of 263 grams) was placed in the test section of the wind tunnel. For this experiment, a total average of 0.0 grams (0% of the soil) were collected downstream of the wind tunnel test section for velocities ranging from 10 mph to 30 mph. The final mass average remaining in the wind tunnel test section at the end of the experiments was 238.5 grams (98.3% of the soil). An average of approximately 4 grams (1.6% of the soil) was airborne and/or was lost through the open back end of the wind tunnel and/or lost due to evaporation effects. Table 21 and Figure 22 provide an average of the data collected during the three experiments.

Table 21 Mass of soil collected at the end of the wind tunnel during experiments with DustBond®

Speed (mph)	DustBond® (7.0:1.0)	DustBond® (1.0:1.0)	DustBond® (0.5:1.0)
	(grams)	(grams)	(grams)
10	0.00	0.00	0.00
15	0.00	0.00	0.00
20	0.00	0.00	0.00
25	0.00	0.00	0.00
28	0.00	0.00	1.00
30	0.00	1.00	2.00

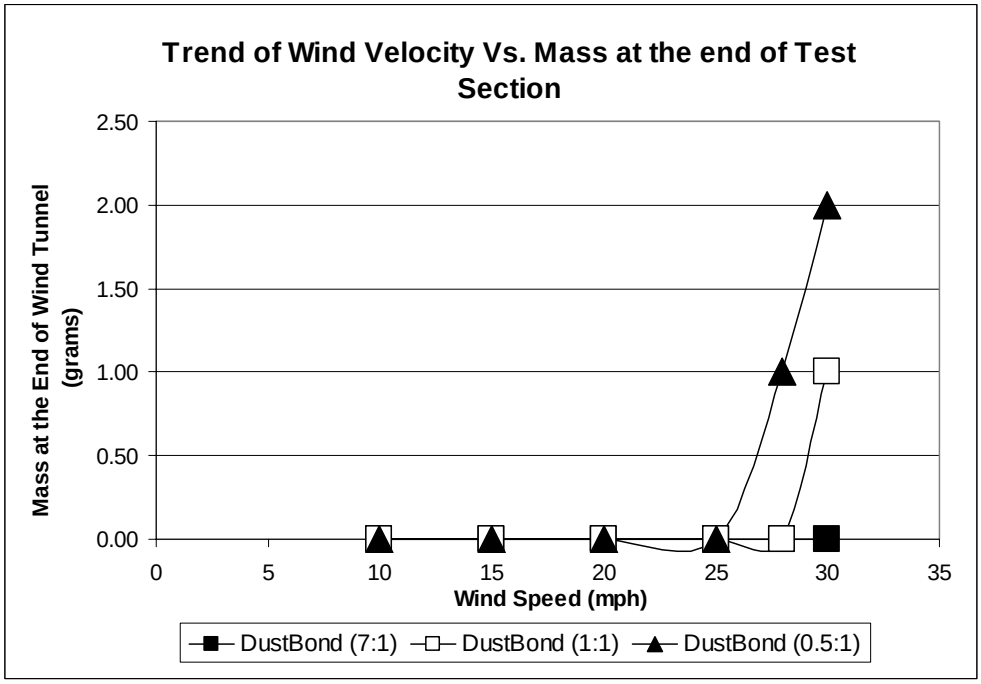

Figure 22 Wind speed vs. mass at end of wind tunnel for DustBond® at 0.5:1.0, 1.0:1.0, and 7.0:1.0 (Water : DustBond®) dilution ratios

Based on the results from these experiments it was determined that the DustBond® provided excellent soil suppression when the soil was exposed to the velocity regimes ranging from 10 to 30 mph. It can be observed from Figure 22 above that there is no soil movement for velocities under 25 mph at dilution ratio of 0.5:1.0 (Water: DustBond®) and only 1 gram of soil was moved at 28 mph for dilution ratio of 1.0:1.0 (Water: DustBond®). No soil movement was recorded/detected at a dilution ratio of 7.0:1.0 (Water : DustBond®). Figures 23 and 24 show a visual representation of the soil movement; it can be observed that there is no detectible (recordable) soil movement from 10 to 30 mph. For these experiments the amount of DustBond® fixatives used was kept constant (4.93 ml) but the amount of water was changed from 7.0:1.0 (Water: DustBond®) to 0.5:1.0 (Water: DustBond®). As presented in Table 10, the amount of water was changed from 34.41 ml (vendor recommended) to 2.465 ml. It could be concluded that the amount of water in the Water: DustBond® solution plays a major role in the suppression of soil particles.

Figure 23 DustBond® dilution ratio of 7.0:1.0 at 10 mph

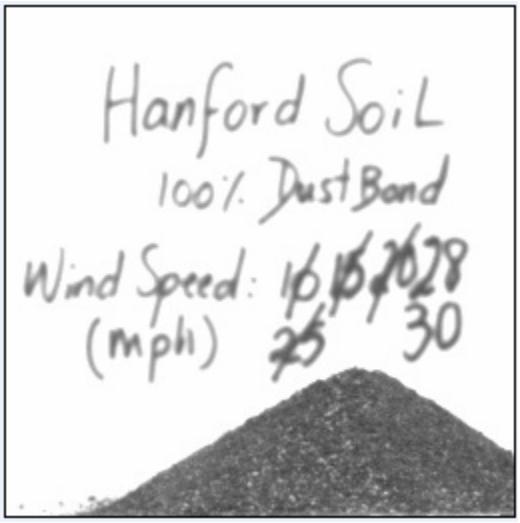

Figure 24 DustBond® dilution ratio of 7.0:1.0 at 30 mph

5.2.4.3 DuraSoil® experiments

For an **application rate of 25% DuraSoil®**, a soil sample of approximately 230 grams (this amount was a little higher than the calculated amount of 227 grams) was placed in the test section of the wind tunnel. For this experiment, a total average of 5.0 grams (2.1% of the soil) was collected downstream of the wind tunnel test section for velocities ranging from 10 to 30 mph. The final average mass remaining in the wind tunnel test section at the end of the experiments was 222.3 grams (96.6% of the soil). An average of approximately 2.6 grams

(1.2% of the soil) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For an **application rate of 50% DuraSoil®**, a soil sample of approximately 231 grams was placed in the test section of the wind tunnel. For this experiment, a total average of 2.0 grams (0.9% of the soil) was collected downstream of the wind tunnel test section for this range in velocities. The final average mass remaining in the wind tunnel test section at the end of the experiments was 226.3 grams (97.9% of the soil). An average of approximately 3.6 grams (1.6% of the soil) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For an **application rate of 100% DuraSoil®** (manufacturer's recommended application rate), a soil sample of approximately 234 grams was placed in the test section of the wind tunnel. For this experiment, a total average of 1.0 grams (0.4% of the soil) were collected respectively downstream of the wind tunnel test section for a velocities ranging from 10 to 30 mph. The final average mass remaining in the wind tunnel test section at the end of the experiments was 229.7 grams (98.1% of the soil). An average of approximately 3.3 grams (1.4% of the soil) was airborne and/or was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

Table 22 and Figure 25 provide an average of the data collected during the three experiments.

Table 22 Mass of soil collected at the end of wind tunnel during experiments with DuraSoil®

Speed (mph)	DuraSoil® Application Rate		
	25.0 %	50.0 %	100.0 %
	(grams)	(grams)	(grams)
10	0.00	0.00	0.00
15	0.00	0.00	0.00
20	0.00	0.00	0.00
25	1.00	0.00	0.00
28	2.00	1.00	0.00
30	2.00	1.00	1.00

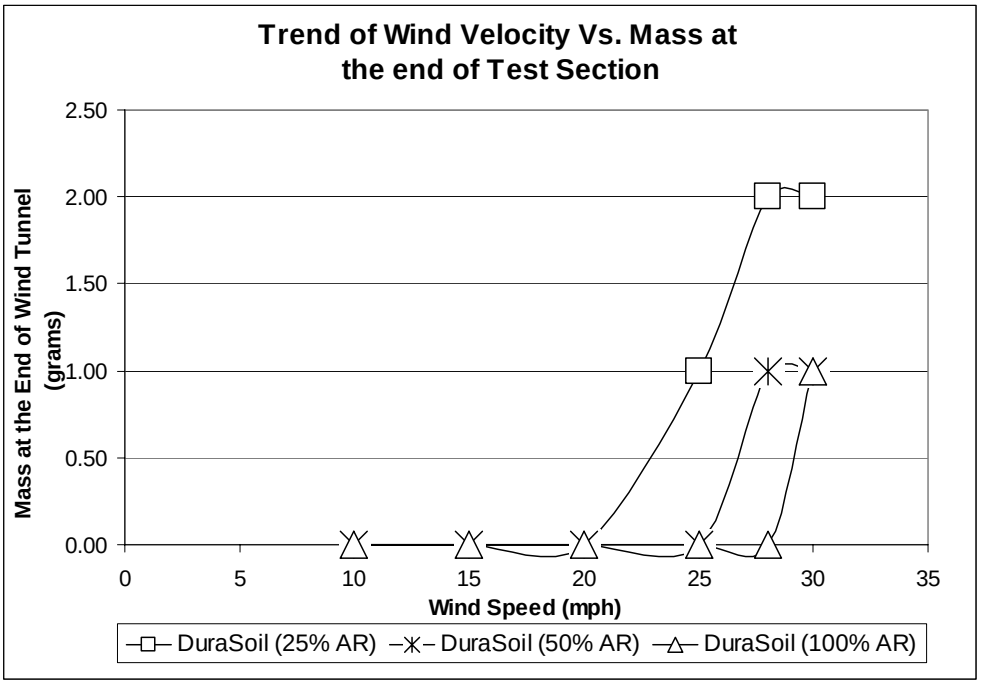

Figure 25 Mass of soil collected at end of wind tunnel for DuraSoil® at different speeds and application rates

Based on the results of these experiments, it was determined that the DuraSoil® also provided excellent soil suppression when the soil was exposed to the velocities ranging from 10 to 30 mph.

5.2.5 PM10 experiments for selected fixatives

PM10 particle size measurements were also collected for Hanford's SP soil treated with the three fixatives (RoadMaster™, DustBond® and DuraSoil®) selected for this study. The same velocity range (10 to 30 mph) was used for these experiments. Table 23 and Figures 26, 27 and 28 show the PM10 concentrations results obtained for all three fixatives tested.

Based on the results from these experiments, the DustBond® fixative showed better performance in suppressing the airborne particulates when compared with the DuraSoil® fixative. This can be observed by comparing the manufacturer's recommended dilution and/or application rates for these two fixatives. For example, at 30 mph, the PM10 concentration for DustBond® was 0.400 mg/m^3 as compared to the results obtained for DuraSoil® (1.480 mg/m^3) at the same wind velocity (30 mph). All things being equal, 73% more PM10 concentration was detected when soil was sprayed with DuraSoil® for the same

velocity (30 mph). When comparing DustBond® to RoadMaster™ with the highest dilution ratio (10%), it can also be seen from the data that DustBond® performed better than RoadMaster™ (0.400 mg/m^3 vs. 0.615 mg/m^3 at 30 mph). It can also be seen from the data that the amount of PM10 generated was increased as the velocity increased; this is true for all three fixatives. It can also be observed that the fixative performance is comparable with the previous results obtained for Hanford's SP soil with 15% and 20% moisture content. Also, manufacturer's recommended concentrations were used for DustBond® and DuraSoil® fixatives (7.0:1.0 and 100% dilution ratio and application rate, respectively). A significant difference in the results was observed at these concentrations.

Table 23 and Figure 26 below show the maximum averaged concentrations obtained for the RoadMaster™ fixative at all velocities tested. It can easily be seen from this figure that as velocity increases, the PM10 concentration also increases for all dilutions rates. On the other hand, as the dilution ratio increased from 2.5% to 10%, the PM10 concentration decreased. At higher dilution ratios, the PM10 concentration is the lowest. This is true for all velocities tested. As the amount of calcium chloride increased, the amount of PM10 generated decreased. Similar trends were observed in the case of DustBond® and DuraSoil® fixatives. These trends are presented in Figures 27 and 28, respectively.

Table 23 PM10 concentrations for Hanford soil with selected fixatives

Speed (mph)	RoadMaster™ (% $CaCl_2$)				DustBond® (water :DustBond®)			DuraSoil® (application rate)		
	2.5%	5.0%	7.5%	10.0%	0.5 : 1.0	1.0 : 1.0	7.0 : 1.0	25%	50%	100%
10	0.237	0.152	0.137	0.051	0.205	0.136	0.098	0.158	0.140	0.139
15	0.249	0.202	0.211	0.110	0.253	0.211	0.098	0.280	0.250	0.230
20	0.354	0.308	0.298	0.262	0.371	0.260	0.160	0.322	0.305	0.280
25	0.459	0.405	0.395	0.366	0.395	0.360	0.269	0.412	0.405	0.380
28	2.923	0.48	0.469	0.288	0.503	0.469	0.370	0.500	0.502	0.495
30	3.097	2.578	1.503	0.615	0.637	1.503	0.400	2.630	1.520	1.480

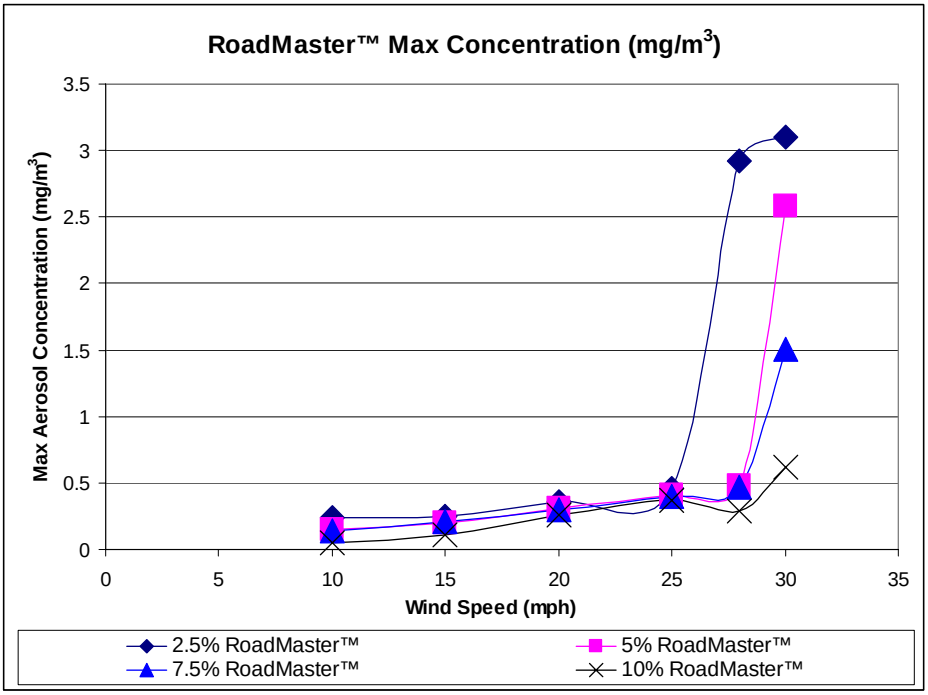

Figure 26 PM10 concentrations – RoadMaster™

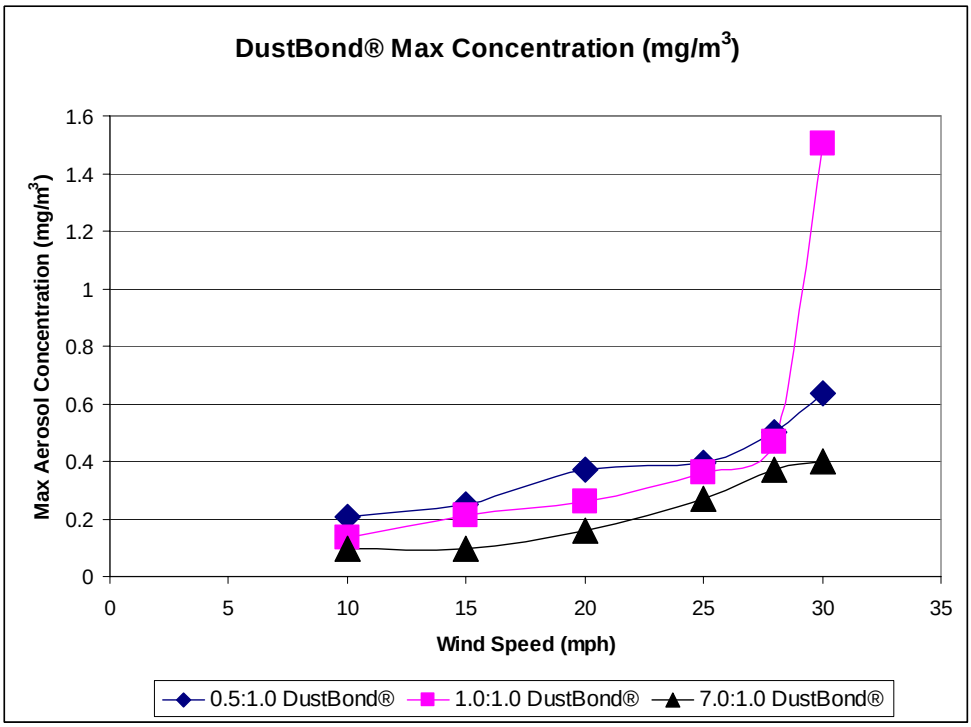

Figure 27 PM10 concentrations – DustBond®

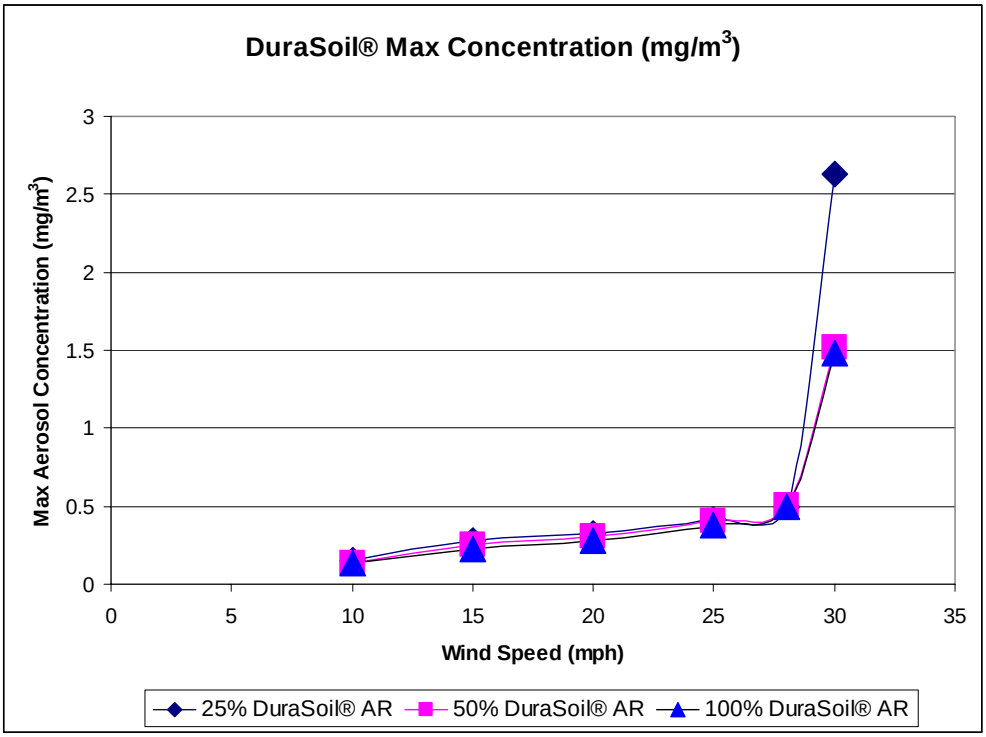

Figure 28 PM10 concentrations – DuraSoil®

5.2.6 Cerium oxide experiments

5.2.6.1 Cerium oxide experiments for soil with 2.7%, 5%, and 20% moisture – mass comparison

For these experiments, the soil mixed with cerium oxide was placed in the test section of an open-loop, low-speed wind tunnel and exposed to free stream wind speeds varying from 10 to 25 mph. The soil matrix was exposed to each velocity regime for a total of 10 minutes. Soil samples with three different percent moistures (2.7%, 5%, and 20%) were used for these tests and were mixed with four different concentrations of cerium oxide (5%, 10%, 15%, and 20%). The cerium oxide was used to simulate plutonium powder contaminantion. The cerium oxide concentration was varied so that conclusions can be drawn on the amount of cerium oxide in the soil vs. the amount of PM10 generated. The effects and interaction of soil moisture and wind velocity were also considered. Also, moisture measurements were not collected at the end of each experiment for the 2.7% moisture case. Instead, the average moisture reported in Section 5.2.1 was used for estimating the unaccounted soil in each experiment. A total of 36 samples were prepared and used for these wind tunnel

experiments. Measurements included the mass displaced due to wind forces and PM10 concentrations.

For **soil with 2.7% moisture**, the initial sample was prepared according to the procedure described in Section 4.1. Four different concentrations of cerium oxide (5%, 10%, 15% and 20%) were mixed with the soil sample containing initial moisture content of 2.7%. The maximum velocity for this experiment was 20 mph instead of 25 mph; the results for these experiments are presented in Table 24. High levels of PM10 concentrations (289.955 mg/m^3) containing cerium oxide were recorded at wind velocities of 20 mph, prompting FIU's EH&S to limit the cerium oxide airborne concentration in the laboratory.

At **5% cerium oxide concentration**, a soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 198 grams (83.9% of the soil). A total of 19 grams (8.0 %) was collected downstream of the wind tunnel test section for velocities ranging from 10 to 20 mph. The percent moisture at the end of the experiment was assumed to be approximately 1.9% (see Section 5.2.1). So, a total of approximately 1.9 grams (0.8%) was lost due to the change in moisture. Approximately 17.1 grams (7.2%) of soil was unaccounted for and believed to have been airborne and/or was lost through the open back end of the wind tunnel.

At **10% cerium oxide concentration**, a soil sample of approximately 247 grams was placed in the wind tunnel test section. The final mass average remaining in the wind tunnel test section at the end of the experiment was 209 grams (15.4%). A total of 12 grams (4.8%) was collected downstream of the wind tunnel test section for velocities ranging from 10 to 20 mph. The percent moisture at the end of the experiment was assumed to be approximately 1.9% (see Section 5.2.1). So, a total of approximately 2.0 grams (0.8%) was lost due to the change in moisture. Approximately 24.0 grams (9.7%) of soil was unaccounted for and believed to have been airborne and/or was lost through the open back end of the wind tunnel.

At **15% cerium oxide concentration**, a soil sample of approximately 259 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 221 grams (14.6 %). A total of 2 grams (0.7%) was

collected downstream of the wind tunnel test section for velocities ranging from 10 to 20 mph. The percent moisture at the end of the experiment was assumed to be approximately 1.9% (see Section 5.2.1). So, a total of approximately 2.1 grams (0.8%) was lost due to the change in moisture. Approximately 34.0 grams (13.1%) of soil was unaccounted for and believed to have been airborne and/or was lost through the open back end of the wind tunnel.

At **20% cerium oxide concentration**, a soil sample of approximately 270 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 221 gram (18.1%). A total of 1 gram (0.4%) was collected downstream of the wind tunnel test section for velocities ranging from 10 to 20 mph. The percent moisture at the end of the experiment was assumed to be approximately 1.9% (see Section 5.2.1). So, a total of approximately 2.2 grams (0.8%) was lost due to the change in moisture. Approximately 46.0 grams (17.0%) of soil was unaccounted for and believed to have been airborne and/or was lost through the open back end of the wind tunnel.

For soil samples containing **5% moisture content and 5% cerium oxide concentration**, a soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 188 grams (79.6% of the soil). A total of 42 grams (17.8% of soil) was collected downstream of the wind tunnel test section for this range of velocities. The percent moisture at the end of the experiment was approximately 3.4%. So a total of approximately 3.8 grams (1.6% of soil) was lost due to moisture effects. Approximately 2.2 grams (0.9%) of soil was airborne and was lost through the open back end of the wind tunnel.

For soil samples containing **5% soil moisture but at 10% cerium oxide concentration**, a sample of approximately 247 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 201 grams (81.4% of soil). A total of 41 grams (16.6% of soil) was collected downstream of the wind tunnel test section for this range of velocities. The percent moisture at the end of the experiment was approximately 3.4%. So, a total of approximately 3.9 grams (1.6% of

soil) was lost due to moisture effects. Approximately 1.1 grams (0.4%) of soil was lost through the open back end of the wind tunnel.

For soil samples containing **5% soil moisture but 15% cerium oxide concentration**, a soil sample of approximately 258 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 200 grams (77.5% of soil). A total of 52 grams (20.2% of soil) was collected downstream of the wind tunnel test section for this range of velocities. The percent moisture at the end of the experiment was approximately 3.4%. So, a total of approximately 4.1 grams (1.6% of soil) was lost due to moisture effects. Approximately 1.9 grams (0.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

The last experiment involved a soil sample with an initial **5% moisture content and a cerium oxide concentration of 20%**. A soil sample of approximately 270 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 202 grams (74.8% of the soil). A total of 61 grams (22.6% of soil) was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 3.4%. So, a total of approximately 4.3 grams (1.6% of soil) was lost due to the change in moisture. Approximately 2.7 grams (1.0%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

At **20% soil moisture content and 5% cerium oxide concentration**, a soil sample of approximately 236 grams was placed in the wind tunnel test section. The final mass average remaining in the wind tunnel test section at the end of the experiment was 232 grams (98.3% of soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 18.5%. So, a total of approximately 3.5 grams (1.5% of soil) was lost due to the change in moisture. Approximately 0.5 grams (0.2%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

At **20% soil moisture content and 10% cerium oxide concentration**, a soil sample of approximately 247grams was placed in the wind tunnel test section. The final average mass

remaining in the wind tunnel test section at the end of the experiment was 239 grams (96.7% of soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 18.5%. So, a total of approximately 3.7 grams (1.5% of soil) was lost due to the change in moisture. Approximately 4.3 grams (1.8%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

At **20% soil moisture content and 15% cerium oxide concentration**, a soil sample of approximately 258 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 250 grams (96.9% of soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 18.5%. So, a total of approximately 3.9 grams (1.5% of soil) was lost due to the change in moisture. Approximately 4.1 grams (1.6%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

At the maximum case of **20% soil moisture and 20% cerium oxide concentration**, a soil sample of approximately 270 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 266 grams (98.5% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 18.5%. So, a total of approximately 4.0 grams (1.5% of soil) was lost due to the change in moisture. For this experiment no airborne was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects. Table 24 presents the results for Hanford SP soil with 2.7%, 5%, and 20% moisture at 20 mph and Table 25 presents the results for Hanford SP soil with 5% and 20% moisture at 25 mph.

Table 24 Averaged mass balance for various cerium oxide and soil moisture concentrations at 20 mph

	2.7% Moisture				5% Moisture				20% Moisture			
	Cerium Oxide %				Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20	5	10	15	20
Initial mass in the test section (grams)	236	247	259	270	236	247	258	270	236	247	258	270
Final mass in the test section (grams)	198	209	221	221	188	201	200	202	232	239	250	266
Total mass of soil collected at the end of Test Section (grams)	19	12	2	1	42	41	52	61	0	0	0	0
Final percent moisture ***	1.9*	1.9	1.9	1.9	3.4	3.4	3.4	3.4	18.5	18.5	18.5	18.5
Mass loss due to moisture (grams)	1.8	2.0	2.1	2.2	3.8	3.9	4.1	4.3	3.5	3.7	3.9	4.0
Total mass of soil unaccounted for (grams)	17.2	24	34	46	2.2	1.1	1.9	2.7	0.5	4.3	4.1	0
Total mass lost†	36.2	36.0	36.0	47.0	44.2	42.1	53.9	63.7	0.5	4.3	4.1	0

***Final percent moisture was not recorded for the 2.7% but was borrowed from Table 15**

† **Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass**

The following section presents the data collected using Hanford's SP soil with 5% and 20% moisture and a maximum velocity of 25 mph. The results for these experiments are presented in Table 25.

At **5% soil moisture content and 5% cerium oxide concentration**, a soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 105 grams (55.5% of the soil). A total of 121 grams (51.2% of soil) was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 3.2%. So a total of approximately 4.3 grams (1.8% of soil) was lost due to moisture effects. Approximately 7.4 grams (3.1%) of soil was airborne and was lost through the open back end of the wind tunnel.

For the soil sample with **5% soil moisture and 10% cerium oxide concentration**, a soil sample of approximately 247 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 114 grams (53.8% of soil). A total of 124 grams (50.2% of soil) was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 3.2%. So, a total of approximately 4.4 grams (1.8% of soil) was lost due to moisture loss. Approximately 4.6 grams (1.9%) of soil was lost through the open back end of the wind tunnel.

For the soil sample with **5% soil moisture content and 15% cerium oxide concentration**, a soil sample of approximately 258 grams was placed in the wind tunnel test section. The final mass average remaining in the wind tunnel test section at the end of the experiment was 110 grams (42.6% of soil). A total of 138 grams (53.4% of soil) was collected downstream of the wind tunnel at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 3.2%. So, a total of approximately 4.6 grams (1.8% of soil) was lost due to moisture change. Approximately 6.1 grams (2.3%) of soil was airborne and was lost through the open back end of the wind tunnel.

The last experiment involved a soil sample with an initial **5% moisture content and 20% cerium oxide concentration**. A soil sample of approximately 270 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 109 grams (40.3% of the soil). A total of 151 grams (55.9% of soil) was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 3.2%. So, a total of approximately 4.8 grams (1.8% of soil) was lost due to the change in moisture. Approximately 5.2 grams (1.9%) of soil was airborne and was lost through the open back end of the wind tunnel.

For soil samples with **20% soil moisture and 5% cerium oxide concentration**, a soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 229 grams (97.0% of soil). A total of 0 grams was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment

was approximately 17.0%. So, a total of approximately 7.0 grams (3.0% of soil) was lost due to the change in moisture. For this experiment, all mass was accounted for.

For samples with **20% soil moisture content and 10% cerium oxide concentration**, a soil sample of approximately 247grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 236 grams (95.5% of soil). A total of 0 grams was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 17.0%. So, a total of approximately 7.4 grams (3.0% of soil) was lost due to the change in moisture. Approximately 3.6 grams (1.4%) of soil was airborne and was lost through the open back end of the wind tunnel.

For samples with **20% soil moisture content and 15% cerium oxide concentration**, a soil sample of approximately 258 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 247 grams (95.7% of soil). A total of 0 grams was collected downstream of the wind tunnel test section at this velocity (25 mph). The final percent moisture at the end of the experiment was approximately 17.0%. So, a total of approximately 7.7 grams (2.9% of soil) was lost due to the change in moisture. Approximately 3.3 grams (1.2%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For samples with **20% moisture and 20% cerium oxide concentration**, a soil sample of approximately 270 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiment was 261 grams (96.6% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. The final percent moisture at the end of the experiment was approximately 17.0%. So, a total of approximately 8.0 grams (2.9% of soil) was lost due to the change in moisture. Approximately 1.0 grams (0.4%) of soil was airborne and was lost through the open back end of the wind tunnel. As previously stated Table 24 presents the results for Hanford SP soil with 2.7%, 5%, 20% moisture at 20 mph and Table 25 presents the results for Hanford SP soil with 5% and 20% moisture at wind velocity of 25 mph.

Table 25 Averaged mass balance for various cerium oxide concentrates and soil moisture of 5% and 20% at 25 mph

	5% Moisture				20% Moisture			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Initial mass in the test section (grams)	236	247	258	270	236	247	258	270
Final mass in the test section (grams)	105	114	110	109	229	236	247	261
Total mass of soil collected at the end of Test Section	121	124	138	151	0	0	0	0
Final percent moisture	3.2	3.2	3.2	3.2	17	17	17	17
Mass loss due to moisture (grams)	4.3	4.4	4.6	4.8	7.0	7.4	7.7	8.0
Total mass of soil unaccounted for (grams)	7.4	4.5	6.1	5.2	0	3.6	3.3	1.0
Total mass lost†	128.4	128.5	144.1	156.2	0	3.6	3.3	1.0

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

5.2.6.2 PM10 cerium oxide experiments for soil with 2.7%, 5%, and 20% moisture

PM10 particle size measurements were collected for Hanford SP soil samples with 2.7%, 5% and 20% moisture and different concentrations of cerium oxide (5%, 10%, 15% and 20%). For these experiments, only the baseline case (2.7% moisture) and two additional soil moistures of 5% and 20% were considered. The maximum velocity for this set of experiments was 20 mph instead of 25 mph. High levels of PM10 concentrations (289.955 mg/m^3) containing cerium oxide were recorded during preliminary experiments, prompting FIU' s EH&S regulations on the cerium oxide airborne concentration in the laboratory. The highest PM10 concentration was 289.955 mg/m^3 and was achieved at a velocity of 20 mph and at a cerium oxide concentration of 20%. The amount of PM10 changed with wind velocity. For example, for a soil sample with initial soil moisture of 2.7% and a cerium oxide concentration of 20%, the PM10 concentration decreased to 54.268 mg/m^3 when the wind velocity was reduced to 15 mph.

It was also noticed that for the same soil moisture (2.7%), as the cerium oxide concentrations increased, the PM10 concentration increased at lower speeds (10 and 15

mph). However at higher speeds (20 mph) there is only a slight increase in PM 10 concentrations as the cerium oxide concentrations increased. At a cerium oxide concentration of 10% and a velocity of 20 mph, the PM10 concentration was 289.937 mg/m^3 but when the wind velocity was maintained constant at 20 mph and the cerium oxide concentration was increased to 20%, the PM10 concentration was almost constant. A graphical representation of the data is presented in Figure 29. Table 26 shows the stated results.

Table 26 PM10 concentrations for soil with 2.7% moisture and varying cerium oxide

	Cerium Oxide Concentration			
	5%	**10%**	**15%**	**20%**
Speed (mph)	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**
10	6.723	13.164	15.450	16.519
15	34.882	38.969	46.075	54.268
20	279.095	289.937	289.935	289.955

An attempt was made to compare Hanford SP soil (2.7% moisture) with and without cerium oxide simulant. Figure 29 compares the baseline case of 2.7% soil moisture for PM10 concentration without cerium oxide (Section 5.2.3) against soil moisture with 2.7% mixed with cerium oxide at different concentrations (5%, 10%, 15% and 20%). It was noticed that for all cases, the PM10 concentrations were higher when cerium oxide was added. At a velocity of 20 mph, the PM10 concentration was 233.390 mg/m^3 (Table 19) for soil without the simulant but when a 5% cerium oxide concentration was added to the soil sample, the PM10 concentration increased to 279.095 mg/m^3. This shows approximately a 16% increase in PM10 concentration. When the cerium oxide concentration was increased even further to 20%, the PM10 concentration increased to an average of 289.955 mg/m^3. This is an increase of approximately 19% when compared to the baseline case (i.e. soil with 2.7% moisture without cerium oxide).

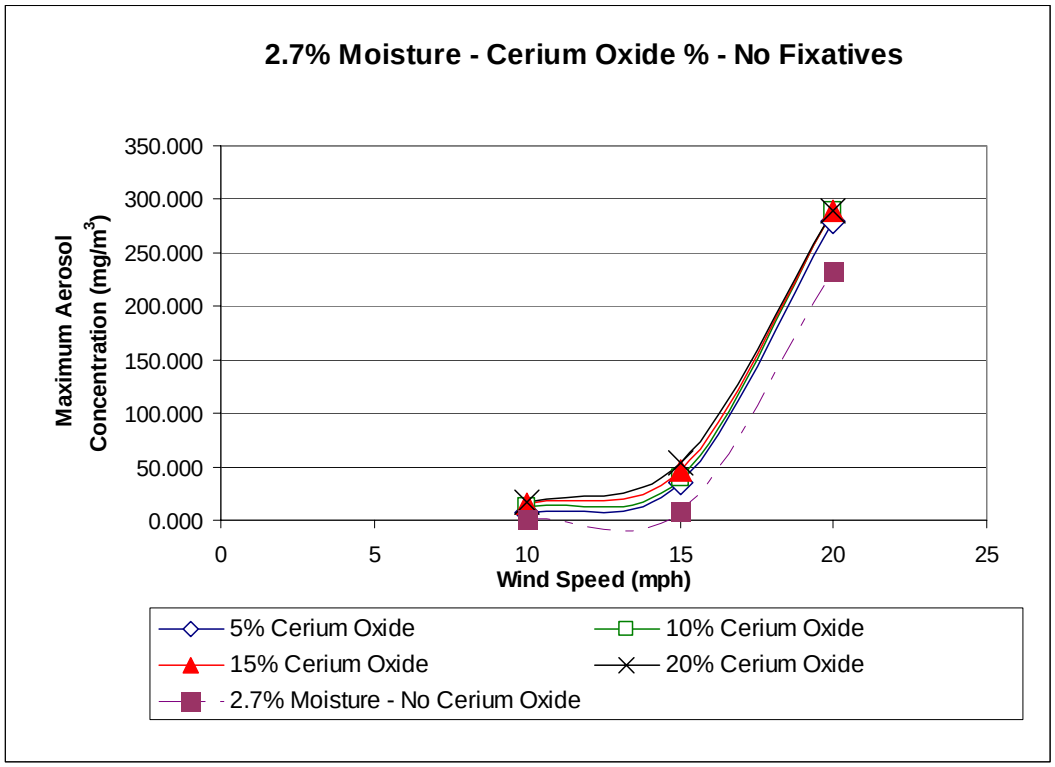

Figure 29 Comparison of soil with 2.7% moisture with and without cerium oxide

PM10 concentrations were collected for soil with **5% moisture** and mixed with four cerium oxide concentrations (5%, 10%, 15% and 20%) for a velocity range from 10 to 25 mph. The largest concentration for soil with 5% moisture and a cerium oxide concentration of 20% was 75.456 mg/m^3 and was recorded at a wind velocity of 25 mph. It was observed that the amount of PM10 generated changed with wind velocity. For the soil with 5% moisture and 20% cerium oxide concentration, at a lower wind velocity of 15 mph, the PM10 concentration was reduced to 54.932 mg/m^3. PM 10 concentrations obtained for soil samples containing 5% moisture are represented in Table 26.

It was also noticed that as the cerium oxide concentration increased, the PM10 concentration increased. For soil with 5% moisture and 10% cerium oxide at a wind velocity of 20 mph, the airborne particulates concentration was 37.623 mg/m^3 (Table 19) but when the cerium oxide concentration increased to 20%, the PM10 concentration increased to 72.568 mg/m^3 at the same wind speed (20 mph). A graphical representation of the data is presented in Figure 30.

An attempt was made to compare soil with 5% moisture, mixed with and without cerium oxide. Figure 30 illustrates this comparison. It was shown that for all cases, the PM10 concentrations were higher when cerium oxide was added to the soil sample. For soil with 5% moisture at a wind velocity of 20 mph, the PM10 concentration was 0.385 mg/m^3 (Table 19) which is very low when compared to the PM 10 concentration of 23.56 mg/m^3 for a soil sample containing 5% cerium oxide (Table 27).

Table 27 PM10 concentrations for soil with 5% moisture mixed with cerium oxide

Simulant	Cerium Oxide Concentration (% by weight)			
Speed (mph)	5%	10%	15%	20%
	(mg/m^3)	(mg/m^3)	(mg/m^3)	(mg/m^3)
10	3.546	22.546	24.879	38.542
15	15.546	28.533	29.890	54.932
20	23.560	37.623	67.580	72.568
25	38.890	51.500	68.789	75.456

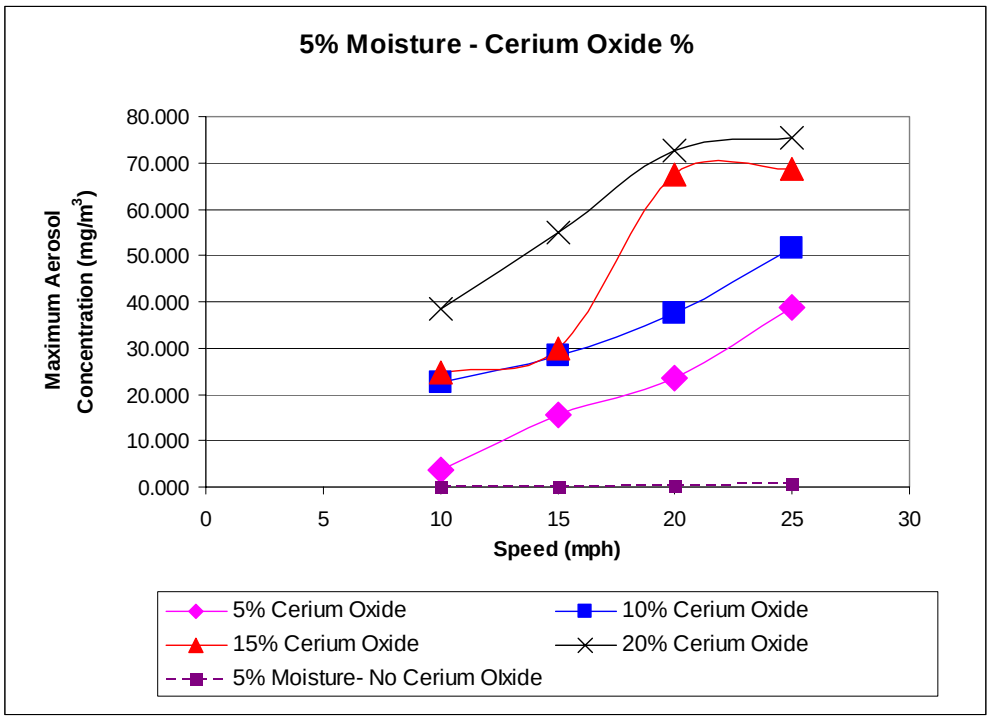

Figure 30 Comparison of 5% soil moisture with and without cerium oxide

PM10 particle size measurements were also collected for soil with 20% initial moisture and different concentrations of cerium oxide (5%, 10%, 15% and 20%) for wind velocities in the range of 10 to 25 mph. Table 28 shows the PM10 concentrations obtained during these

experiments and is shown graphically in Figure 31. The largest PM10 concentration of 5.456 mg/m^3 was recorded at 25 mph for the 20% cerium oxide concentration. It was noted that the amount of PM10 concentration increased with increasing wind velocity. For the sample having soil moisture of 20% and cerium oxide concentration of 20%, when exposed to a lower wind force of 15 mph, the PM10 concentration decreased to 1.456 mg/m^3. This represents a 74% reduction in PM10 concentration when the wind velocity was reduced by a 25%.

It was also noticed that for soil with 20% moisture, as the cerium oxide percentage increased, the amount of airborne particulates increased. For 20% soil moisture with 10% cerium oxide, at a velocity of 20 mph, the airborne concentration was 0.754 mg/m^3 which is approximately 50% when compared to the soil sample having a cerium oxide concentration of 20% (1.678 mg/m^3).

Table 28 PM10 concentrations for soil with 20% moisture and varying cerium oxide concentrations

Simulant	Cerium Oxide			
Speed (mph)	5%	10%	15%	20%
	(mg/m^3)	(mg/m^3)	(mg/m^3)	(mg/m^3)
10	0.124	0.154	0.245	0.356
15	0.345	0.423	0.654	1.456
20	0.573	0.754	0.945	1.678
25	1.243	1.987	2.546	5.456

A comparison of PM 10 concentration was made between the 20% moisture soil samples mixed with and without the addition of cerium oxide. It was shown that tPM10 concentrations were higher for the samples mixed with cerium oxide. For example, for soil with 20% soil moisture and at a velocity of 20 mph, the airborne concentration was 0.142 mg/m^3 (Table 19) but when 5% of cerium oxide (minimum case) was added to the soil containing 20% moisture, the airborne concentration increased to 0.573 mg/m^3 at the same speed 20 mph. Figure 31 shows this comparison.

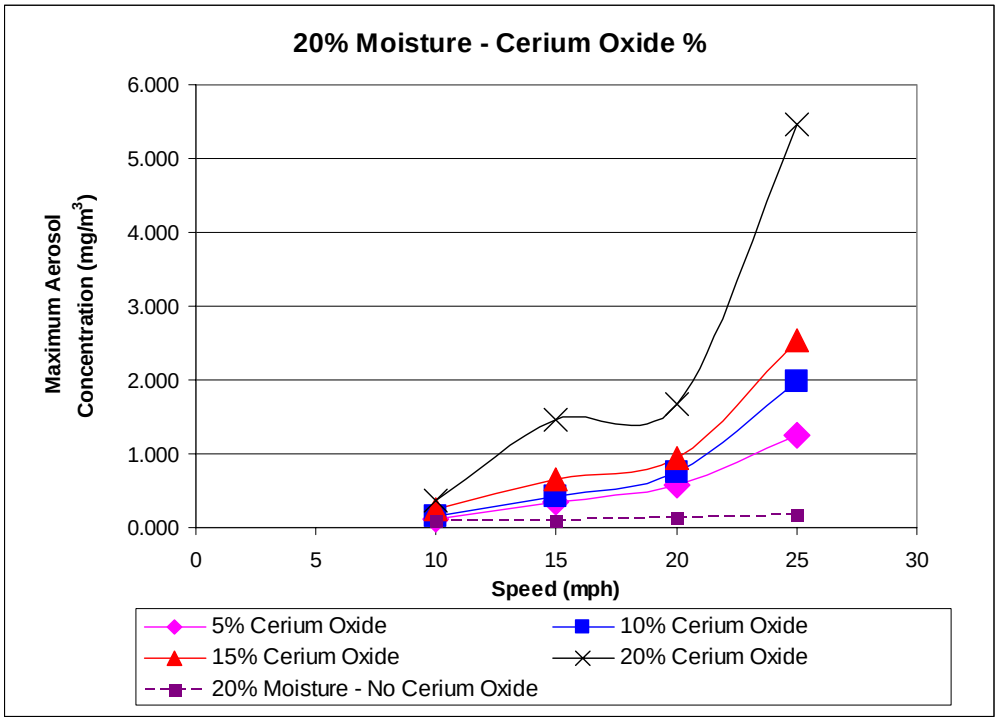

Figure 31 Comparison of 20% soil moisture with and without cerium oxide

5.2.6.3 RoadMaster™/cerium oxide experiments – mass balance

For this experiment, soil samples (with initial moisture content of 2.7%) were sprayed with two dilution ratios of RoadMaster™, mainly 2.5% (a low end) and 10% (a high end). The samples were then mixed with four different concentrations of cerium oxide simulant (5%, 10%, 15% and 20%). The procedures to prepare the soil samples containing the RoadMaster™ fixatives and mixing it cerium oxide concentrations were described in Section 4.3. The change in percent moisture was not measured for these experiments. The data collected during these experiments is presented in Table 29.

For **RoadMaster™ dilution ratio of 2.5% and mixed with 5% cerium oxide** concentration, an initial soil sample of approximately 235 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 231 grams (98.3% of the soil). No soil (0 grams) was collected at the back end of the wind tunnel. Approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **RoadMaster™ dilution ratio of 2.5% and mixed with 10% cerium oxide** concentration, an initial soil sample of approximately 234 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 230 grams (98.2% of the soil). Approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 2.5% and mixed with 15% cerium oxide** concentration, an initial soil sample of approximately 234 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 229 grams (97.8% of the soil). Approximately 5 grams (2.1%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 2.5% and mixed with 20% cerium oxide** concentration, an initial soil sample of approximately 234 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 229 grams (97.8% of the soil). Approximately 5 grams (2.1%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 10% and mixed with 5% cerium oxide concentration**, an initial soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 232 grams (98.3% of the soil). An average of approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 10% and mixed with 10% cerium oxide** concentration, an initial soil sample of approximately 234 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 230 grams (98.2% of the soil). An average of approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 10% and mixed with 15% cerium oxide** concentration, an initial soil sample of approximately 235 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 231 grams (98.3% of the soil). Approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **RoadMaster™ with dilution ratio of 10% and mixed with 20% cerium oxide** concentration, an initial soil sample of approximately 235 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 231 grams (98.3% of the soil). Approximately 4 grams (1.7%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects. Table 29 represents the summary of the results.

Table 29 Mass balance for RoadMaster™ concentrations of 2.5% and 10% mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

	2.7% Moisture				2.7% Moisture			
	RoadMaster™ (2.5%)				RoadMaster™ (10%)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Initial mass in the test section (grams)	235	234	234	234	236	234	235	235
Final mass in the test section (grams)	231	230	229	229	232	230	231	231
Total mass of soil collected at the end of Test Section (grams)	0	0	0	0	0	0	0	0
Total mass of soil unaccounted for (grams)	4	4	5	5	4	4	4	4
Total mass lost†	4	4	5	5	4	4	4	4

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

5.2.6.4 PM10 concentrations experiments for RoadMaster™ mixed with cerium oxide

Table 30 and Figures 32 and 33 the results obtained for RoadMaster™ with dilution ratios of 2.5% and 10% mixed with varying cerium oxide dilute ratios (ranging from 5% to 20%). For both RoadMaster™ dilution ratios, it can be seen from Table 29 that as the velocity

increased, the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For RoadMaster™ at a dilution ratio of 2.5% and at 20% cerium oxide, the PM10 concentration varied from 0.203 mg/m^3 to 9.123 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher RoadMaster™ dilution ratio of 10% and a cerium oxide concentration of 20%. In this case, the PM10 concentration increased from 0.188 mg/m^3 to 5.245 mg/m^3 when the velocity was increased from 10 mph to 25 mph. It can be observed that the PM10 concentration decreased as the dilution ratios of RoadMaster™ increased from 2.5% to 10%. The PM10 concentration decreased from 9.123 mg/m^3 to 5.245 mg/m^3 for the same velocity range of 25 mph. Similar trends were noticed for the other velocity ranges. Figures 32 and 33 below also compare the PM10 generation for the two RoadMaster™ dilution ratios (2.5% and 10%) with and without cerium oxide simulant. For both cases, it can be seen that there was a significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

Table 30 PM10 concentrations for RoadMaster™ fixative mixed with cerium oxide

Moisture %	**2.7%**				**2.7%**			
Fixative	**RoadMaster™ 2.5%**				**RoadMaster™ 10%**			
Simulant	**Cerium Oxide**				**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**	**5%**	**10%**	**15%**	**20%**
10	0.207	0.128	0.189	0.203	0.085	0.120	0.178	0.188
15	0.323	0.350	0.375	1.269	0.301	0.352	0.367	1.192
20	0.380	0.410	0.450	1.906	0.307	0.404	0.410	0.861
25	1.298	2.653	8.385	9.123	0.497	0.677	3.447	5.245

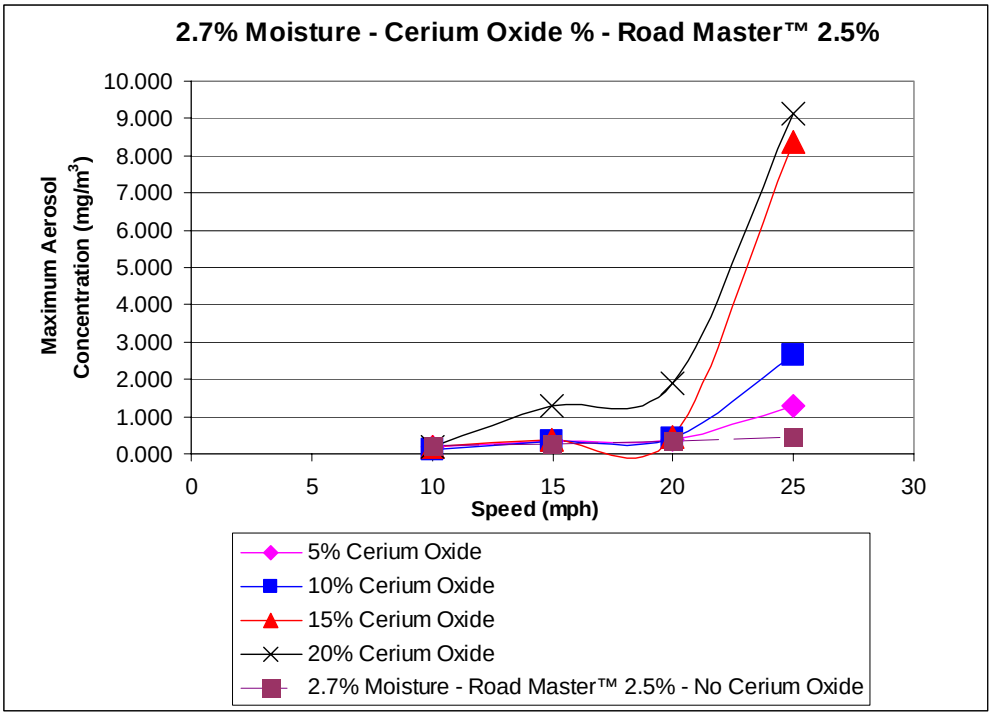

Figure 32 PM 10 concentrations for 2.5% RoadMaster™ with and without cerium oxide simulant

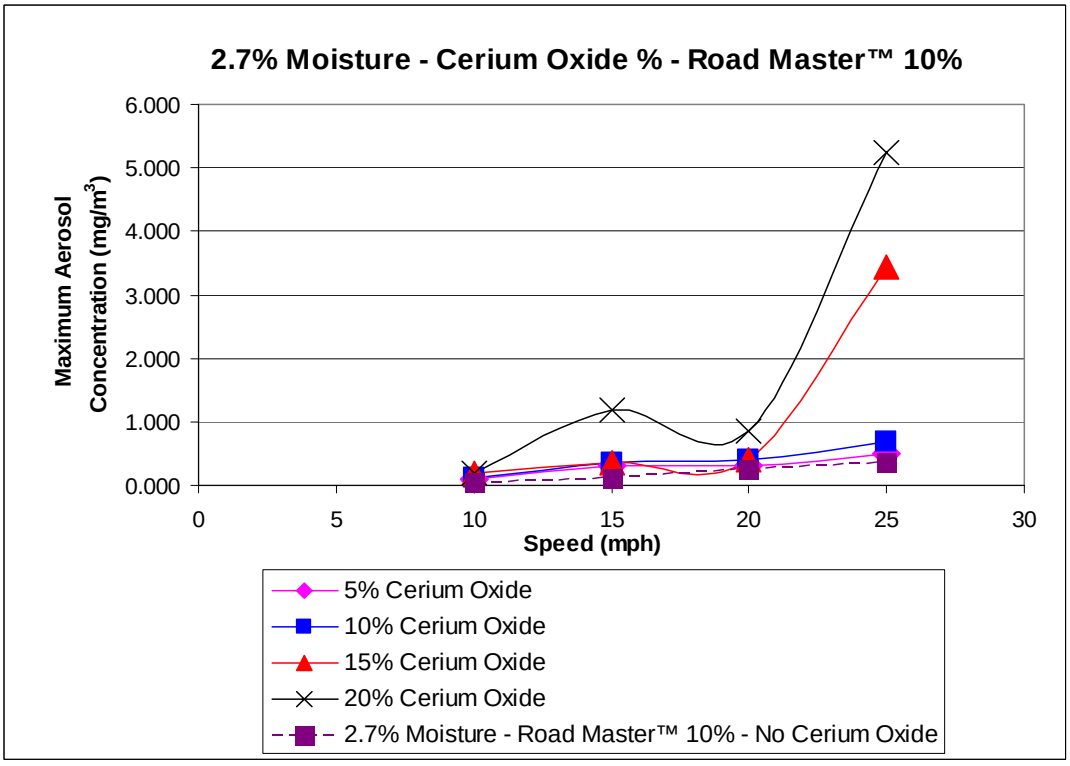

Figure 33 PM 10 concentrations for 10% RoadMaster™ with and without cerium oxide simulant

5.2.6.5 DustBond®/cerium oxide experiments – mass balance

For this experiment, soil samples (with initial moisture content of 2.7%) were sprayed with DustBond® dilution ratios of 0.5:1.0 and 7.0:1.0 (Water: DustBond®). The samples were then mixed with four different concentrations of cerium oxide simulant (5%, 10%, 15% and 20%). The procedures to prepare the soil samples containing the DustBond® fixative and mixing it with 5%, 10%, 15% and 20% cerium oxide concentrations were described in Section 4.3. The moisture at the end of the experiments was not measured during these experiments. The data collected during these experiments is presented in Table 31 below.

For **DustBond® with dilution ratio of 0.5:1.0 (Water: DustBond®) and mixed with a 5% cerium oxide** concentration, an initial soil sample of approximately 236 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 233 grams (98.7% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. Approximately 3 grams (1.2%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **DustBond® with dilution ratio of 0.5:1.0 (Water: DustBond®) and mixed with a 10% cerium oxide** concentration, an initial soil sample of approximately 232 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 221 grams (95.2% of the soil). A total of 6 grams (2.5%) of soil was collected downstream of the wind tunnel test section for this range of velocities. Approximately 5 grams (2.1%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **DustBond® with dilution ratio of 0.5:1.0 (Water: DustBond®) and mixed with a 15% cerium oxide** concentration, an initial soil sample of approximately 233 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 229 grams (98.2% of the soil). A total of 1 gram (0.4%) of soil was collected downstream of the wind tunnel test section for this range of velocities. Approximately 3 grams (1.2%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **DustBond® with dilution ratio of 0.5:1.0 (Water: DustBond®) and mixed with a 20% cerium oxide** concentration, an initial soil sample of approximately 232 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 228 grams (98.2% of the soil). A total of 2 grams (0.8%) was collected downstream of the wind tunnel test section for this range of velocities. Approximately 2 grams (0.8%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **DustBond® with dilution ratio of 7.0:1.0 (Water: DustBond®) and mixed with a 5% cerium oxide concentration**, an initial soil sample of approximately 260 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 253 grams (97.3% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. Approximately 7 grams (0.4%) of soil was airborne and was lost through the open back end of the wind tunnel and/or was lost due to evaporation effects.

For **DustBond® with dilution ratio of 7.0:1.0 (Water: DustBond®) and mixed with a 10% cerium oxide** concentration, an initial soil sample of approximately 263 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 258 grams (98.1% of the soil)). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. Approximately 5 grams (1.9%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DustBond® with dilution ratio of 7.0:1.0 (Water: DustBond®) and mixed with a 15% cerium oxide** concentration, an initial soil sample of approximately 262 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 254 grams (96.9% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. Approximately 8 grams (3.0%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DustBond® with dilution ratio of 7.0:1.0 (Water: DustBond®) and mixed with a 20% cerium oxide** concentration, an initial soil sample of approximately 262 grams was placed in

the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 255 grams (97.3% of the soil). A total of 0 grams was collected downstream of the wind tunnel test section for this range of velocities. Approximately 5 grams (1.9%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

Table 31 Mass balance for DustBond® dilutions of 0.5:1.0 and 7.0:1.0 mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

	2.7% Moisture				2.7% Moisture			
	DustBond® (0.5:1.0)				DustBond® (7.0:1.0)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Initial mass in the test section (grams)	236	232	233	232	260	263	262	262
Final mass in the test section (grams)	233	221	229	228	253	258	254	255
Total mass of soil collected at the end of Test Section (grams)	0	6	1	2	0	0	0	0
Total mass of soil unaccounted for (grams)	3	5	3	2	7	5	8	5
Total mass lost†	3	11	4	4	7	5	8	5

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

5.2.6.6 PM10 concentrations experiments for DustBond® mixed with cerium oxide

Table 32 and Figures 34 and 35 compare the results obtained for two DustBond® dilution ratios of 0.5:1.0 and 7.0:1.0 (Water: DustBond®) mixed with varying cerium oxide concentrations ranging from 5% to 20%. For both DustBond® concentrations, it can be seen from Table 31 that as the velocity increased, the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For a DustBond® dilution ratio of 0.5:1.0 and a cerium oxide concentration of 20%, the PM10 concentration varied from 0.156 mg/m^3 to 7.891 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher DustBond® dilution ratio of 7.0:1.0 and the same cerium oxide concentration of 20%. In this case, the PM10 concentration increased from 0.099 mg/m^3 to 3.545 mg/m^3 when the velocity was increased from 10 mph to 25 mph. At the

same time, it can be observed that the PM10 concentration decreased as the dilution ratio of DustBond® increased from 0.5:1.0 to 7.0:1.0. Examining the previous example, the PM10 concentration decreased from 7.891 mg/m^3 to 3.545 mg/m^3 for the same velocity range of 25 mph. Similar trends were noticed for the other velocity ranges. Figures 34 and 35 below also compare the PM10 generation for the two DustBond® dilution ratios (0.5:1.0 to 7.0:1.0) with and without cerium oxide simulant. For both cases, it can be seen that there was a significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

Table 32 PM10 concentrations for DustBond® fixative mixed with cerium oxide

Moisture %	2.7%				2.7%			
Fixative %	DustBond® (0.5:1)				DustBond® (7:1)			
Simulant	Cerium Oxide				Cerium Oxide			
Speed (mph)	5%	10%	15%	20%	5%	10%	15%	20%
10	0.088	0.099	0.123	0.156	0.075	0.079	0.087	0.099
15	0.215	0.315	0.327	0.987	0.287	0.325	0.366	0.435
20	0.401	0.467	0.524	0.875	0.305	0.355	0.388	0.555
25	0.420	5.455	6.545	7.891	0.450	0.521	1.523	3.545

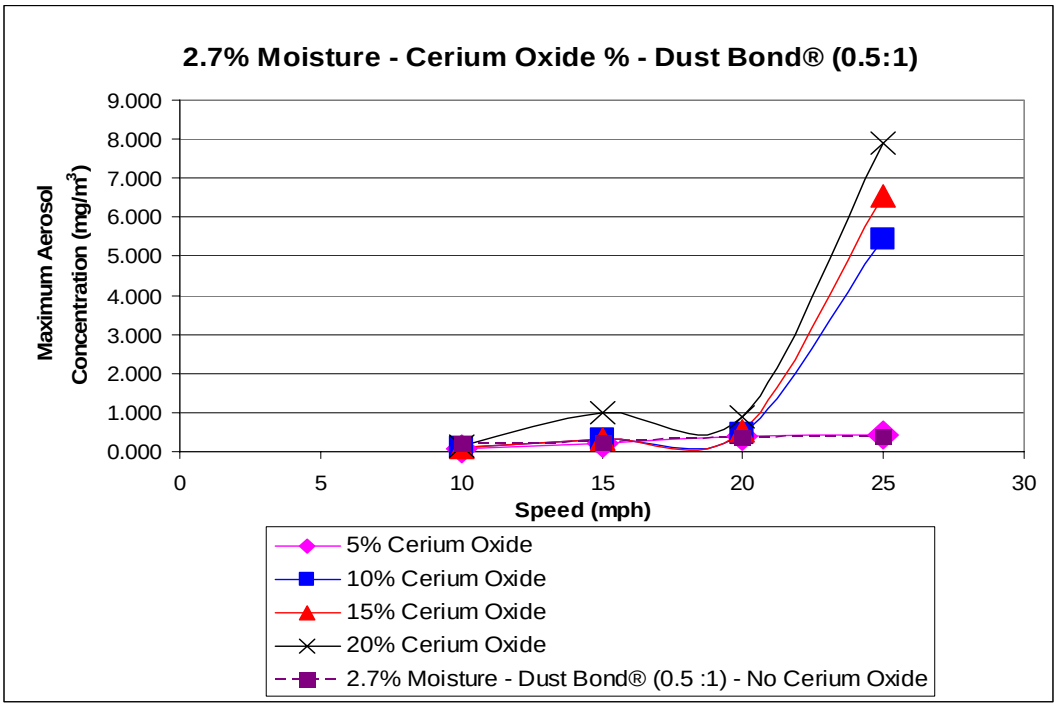

Figure 34 PM 10 concentrations for 0.5:1.0 DustBond® with and without cerium oxide simulant

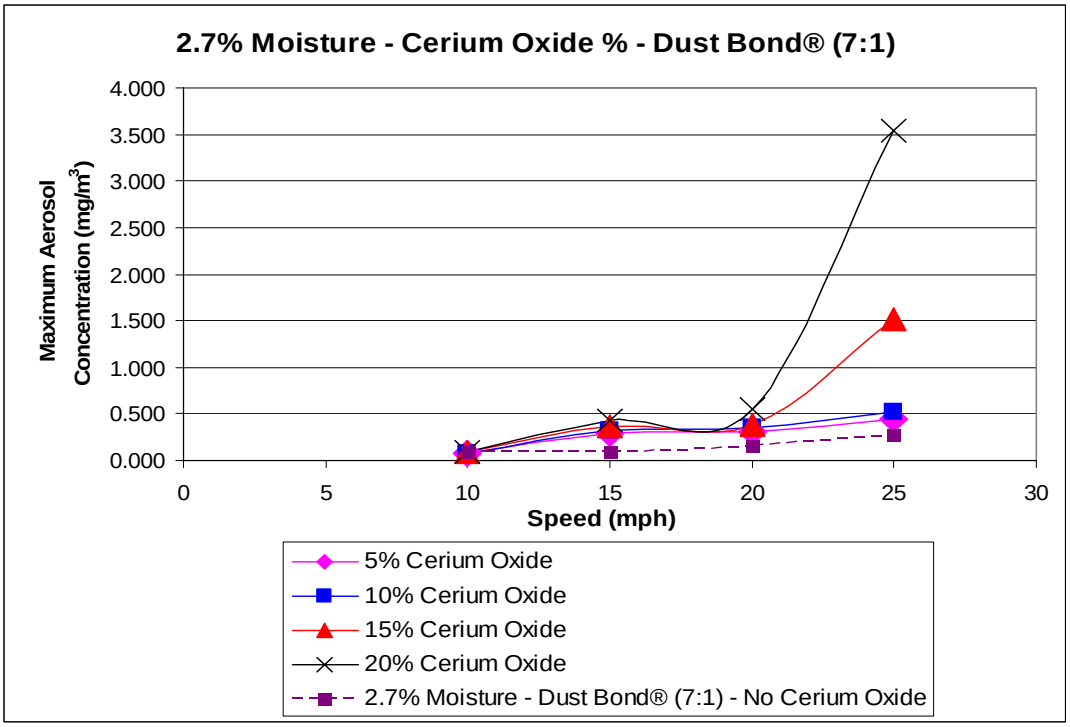

Figure 35 PM 10 concentrations for 7.0:1.0 DustBond® with and without cerium oxide simulant

5.2.6.7 DuraSoil®/cerium oxide experiments – mass balance

For this experiment, soil samples (with initial moisture content of 2.7%) were sprayed with two DuraSoil® application rates of 25% and 100%. The samples were then mixed with four different concentrations of cerium oxide simulant (5%, 10%, 15% and 20%). The procedures to prepare the soil samples containing the DuraSoil® fixative and mixing it with 5%, 10%, 15% and 20% cerium oxide concentrations were described in Section 4.3. The moisture at the end of the experiments was not colleted. The data collected during these experiments is presented in Table 33.

For **DuraSoil® with application ratio of 25% and mixed with a 5% cerium oxide** concentration, an initial soil sample of approximately 227 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 194 grams (85.4% of the soil). A total of 32 grams (14.0% of the soil) was collected downstream of the wind tunnel test section for velocities ranging from 10 to 25 mph. Approximately 1 gram (0.4%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DuraSoil® with application ratio of 25% and mixed with a 10% cerium oxide** concentration, an initial soil sample of approximately 228 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 191 grams (83.7% of the soil). A total of 34 grams (14.9% of the soil) was collected downstream of the wind tunnel test section for this range of velocities. Approximately 3 grams (1.3% of the soil) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DuraSoil® with application ratio of 25% and mixed with a 15% cerium oxide** concentration, an initial soil sample of approximately 227 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 214 grams (94.2% of the soil). A total of 10 grams (4.4% of the soil) was collected downstream of the wind tunnel test section for this range of velocities. Approximately 3 grams (1.3%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DuraSoil® with application ratio of 25% and mixed with a 20% cerium oxide** concentration, an initial soil sample of approximately 227 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 223 grams (98.2% of the soil). A total of 2 grams (0.8%) was collected downstream of the wind tunnel test section for this range of velocities. Approximately 2 grams (0.8%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DuraSoil® with application ratio of 100% and mixed with a 5% cerium oxide** concentration, an initial soil sample of approximately 235 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 235 grams (100.0% of the soil). A total of 0 grams of the soil was collected downstream of the wind tunnel test section for this range of velocities. All mass was accounted for in this experiment.

For **DuraSoil® with application ratio of 100% and mixed with a 10% cerium oxide** concentration, an initial soil sample of approximately 234 grams was placed in the wind

tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 234 grams (100.0% of the soil). A total of 0 grams of the soil was collected downstream of the wind tunnel test section for this range of velocities. All mass was accounted for in this experiment.

For **DuraSoil® with application ratio of 100% and mixed with a 15% cerium oxide** concentration, an initial soil sample of approximately 235 grams was placed in the wind tunnel test section. The final mass remaining in the wind tunnel test section at the end of the experiments was 232 grams (98.7% of the soil). A total of 2 grams (0.8% of the soil) was collected downstream of the wind tunnel test section for this range of velocities. Approximately 1 grams (0.4%) of soil was airborne and was lost through the open back end of the wind tunnel and/or lost due to evaporation effects.

For **DuraSoil® with application ratio of 100% and mixed with a 20% cerium oxide** concentration, an initial soil sample of approximately 236 grams was placed in the wind tunnel test section. The final average mass remaining in the wind tunnel test section at the end of the experiments was 234 grams (99.1% of the soil). A total of 2 grams (0.8%) was collected downstream of the wind tunnel test section for this range. All mass was accounted for in this experiment once rounding errors were taken into account.

Table 33 Mass balance for DuraSoil® with application ratios of 25% and 100% mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

	2.7% Moisture				2.7% Moisture			
	DuraSoil® (25% AR)				DuraSoil® (100% AR)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Initial mass in the test section (grams)	227	228	227	227	235	234	235	236
Final mass in the test section (grams)	194	191	214	223	235	234	232	234
Total mass of soil collected at the end of Test Section (grams)	32	34	10	2	0	0	2	2
Total mass of soil unaccounted for (grams)	1	3	3	2	0	0	1	0
Total mass lost†	33	37	13	4	0	0	3	2

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

5.2.6.8 PM10 concentrations for DuraSoil® mixed with cerium oxide

Table 34 and Figures 36 and 37 compare the results obtained for two DuraSoil® application ratios of 25% and 100% and mixed with varying cerium oxide concentrations ranging from 5% to 20%. For both DuraSoil® application ratios, it can be seen from Table 33 that as the velocity increased, the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For DuraSoil® with 25% application ratio and a cerium oxide concentration of 20%, the PM10 concentration varied from 0.978 mg/m^3 to 286.652 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher DuraSoil® application ratio of 100% and the same cerium oxide concentration of 20%. In this case the PM10 concentration increased from 0.654 mg/m^3 to 12.456 mg/m^3 when the velocity was increased from 10 mph to 25 mph. it can be observed that the PM10 concentration decreased as the dilution ratio of DuraSoil® increased from 25% to 100%. Similar trends were noticed for the other velocity ranges. Figures 36 and 37 also compare the PM10 generation for the two DuraSoil® application ratios (25% and 100%) with and without cerium oxide simulant. For both cases, it can be seen that there was a

significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

Table 34 PM10 concentrations for DuraSoil® fixative mixed with cerium oxide

Moisture %	2.7%				2.7%			
Fixative %	DuraSoil® (25% AR)				DuraSoil® (100% AR)			
Simulant	Cerium Oxide				Cerium Oxide			
Speed (mph)	5%	10%	15%	20%	5%	10%	15%	20%
10	0.598	0.754	0.865	0.978	0.231	0.353	0.423	0.654
15	15.456	16.475	19.545	20.875	0.335	0.433	0.559	0.752
20	30.355	32.450	35.556	39.492	0.385	1.611	1.856	2.546
25	271.368	278.697	278.992	286.652	0.461	8.403	9.487	12.456

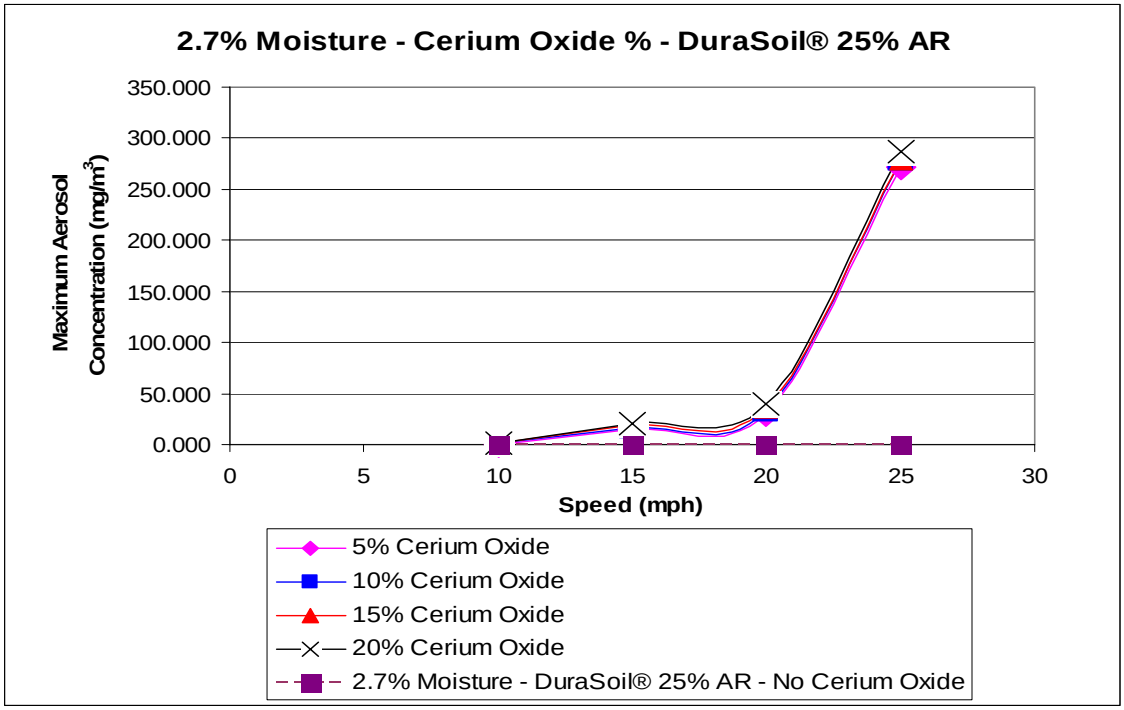

Figure 36 PM 10 concentrations for 25% DuraSoil® with and without cerium oxide simulant

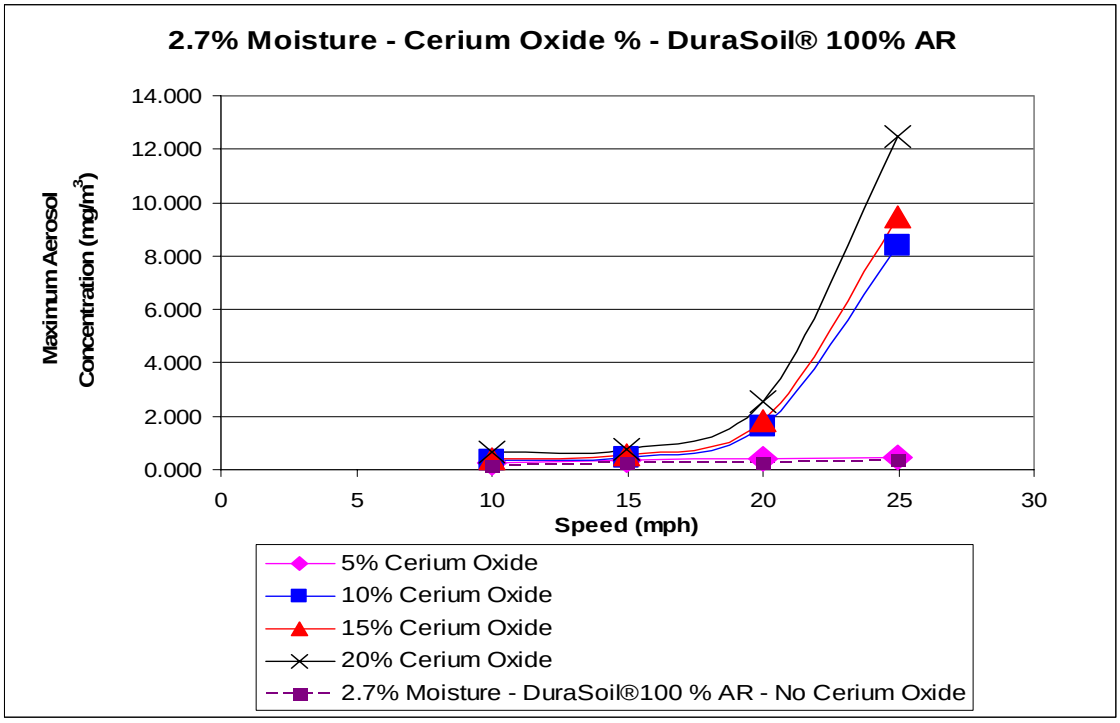

Figure 37 PM 10 concentrations for 100% DuraSoil® with and without cerium oxide simulant

5.2.7 Summary of results for cerium oxide simulant

This section provides a summary of the results obtained for mass loss and PM10 concentration experiments for soil with cerium oxide concentrations of 5%, 10%, 15%, and 20%. Table 35 shows the results for soil with varying percent moisture (2.7%, 5%, and 20%) mixed with 4 cerium oxide concentrations at 20 mph. Table 36 summarizes the results for soil/ fixatives matrices (RoadMaster™, DustBond®, and DuraSoil®) mixed with 4 cerium oxide concentrations at 20 mph. PM10 results are shown in Tables 37 and 38. Table 36 summarizes PM10 concentrations for soil with varying percent moistures mixed with 4 cerium oxide concentrations at a velocity range of 10 to 20 mph. Finally, Table 38 presents the results for soil/fixative matrix mixed with 4 cerium oxide concentrations at a velocity range of 10 to 25 mph.

Table 35 Averaged mass balance for various cerium oxide and soil moisture concentrations at 20 mph

	2.7% Moisture				5% Moisture				20% Moisture			
	Cerium Oxide %				Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20	5	10	15	20
Total mass of soil collected at the end of Test Section (grams)	19	12	2	1	42	41	52	61	0	0	0	0
Total mass of soil unaccounted for (grams)	17.2	24	34	46	2.2	1.1	1.9	2.7	0.5	4.3	4.1	0
Total mass lost†	36.2	36.0	36.0	47.0	44.2	42.1	53.9	63.7	0.5	4.3	4.1	0

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

Table 36 Averaged mass balance for various cerium oxide and soil/fixative matrix concentrations at 20 mph

	2.7% Moisture							
	RoadMaster™ (2.5%)				RoadMaster™ (10%)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Total mass of soil collected at the end of Test Section (grams)	0	0	0	0	0	0	0	0
Total mass of soil unaccounted for (grams)	4	4	5	5	4	4	4	4
Total mass lost†	4	4	5	5	4	4	4	4
	DustBond® (0.5:1.0)				DustBond® (7.0:1.0)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Total mass of soil collected at the end of Test Section (grams)	0	6	1	2	0	0	0	0
Total mass of soil unaccounted for (grams)	3	5	3	2	7	5	8	5
Total mass lost†	3	11	4	4	7	5	8	5
	DuraSoil® (25% AR)				DuraSoil® (100% AR)			
	Cerium Oxide %				Cerium Oxide %			
	5	10	15	20	5	10	15	20
Total mass of soil collected at the end of Test Section (grams)	32	34	10	2	0	0	2	2
Total mass of soil unaccounted for (grams)	1	3	3	2	0	0	1	0
Total mass lost†	33	37	13	4	0	0	3	2

† Total mass lost is the sum of mass collected at end of wind tunnel and unaccounted mass

Table 37 PM10 concentrations for soil with varying percent moisture mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

Moisture %	**2.7% Base Moisture**			
Fixative	**Non**			
Simulant	**Cerium Oxide**			
	5%	**10%**	**15%**	**20%**
Speed (mph)	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**
10	6.723	13.164	15.45	16.519
15	34.882	38.969	46.075	54.268
20	279.095	289.937	289.935	289.955
Moisture %	**5.00%**			
Fixative	**Non**			
Simulant	**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**
	(mg/m^3)	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**
10	3.546	22.546	24.879	38.542
15	15.546	28.533	29.89	54.932
20	23.56	37.623	67.58	72.568
25	38.89	51.5	68.789	75.456
Moisture %	**20.00%**			
Fixative	**Non**			
Simulant	**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**
	(mg/m^3)	**(mg/m^3)**	**(mg/m^3)**	**(mg/m^3)**
10	0.124	0.154	0.245	0.356
15	0.345	0.423	0.654	1.456
20	0.573	0.754	0.945	1.678
25	1.243	1.987	2.546	5.456

Table 38 PM10 concentrations for soil/fixative matrix mixed with cerium oxide concentrations of 5%, 10%, 15%, and 20%

Moisture %	2.7% Base Moisture							
Fixative	**RoadMaster™ 2.5%**				**RoadMaster™ 10%**			
Simulant	**Cerium Oxide**				**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**	**5%**	**10%**	**15%**	**20%**
10	0.207	0.128	0.189	0.203	0.085	0.12	0.178	0.188
15	0.323	0.35	0.375	1.269	0.301	0.352	0.367	1.192
20	0.38	0.41	0.45	1.906	0.307	0.404	0.41	0.861
25	1.298	2.653	8.385	9.123	0.497	0.677	3.447	5.245
Fixative	**DustBond® (0.5:1.0)**				**DustBond® (7.0:1.0)**			
Simulant	**Cerium Oxide**				**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**	**5%**	**10%**	**15%**	**20%**
10	0.088	0.099	0.123	0.156	0.075	0.079	0.087	0.099
15	0.215	0.315	0.327	0.987	0.287	0.325	0.366	0.435
20	0.401	0.467	0.524	0.875	0.305	0.355	0.388	0.555
25	0.42	5.455	6.545	7.891	0.45	0.521	1.523	3.545
Fixative	**DuraSoil® (25% AR)**				**DuraSoil® (100% AR)**			
Simulant	**Cerium Oxide**				**Cerium Oxide**			
Speed (mph)	**5%**	**10%**	**15%**	**20%**	**5%**	**10%**	**15%**	**20%**
10	0.598	0.754	0.865	0.978	0.231	0.353	0.423	0.654
15	15.456	16.475	19.545	20.875	0.335	0.433	0.559	0.752
20	30.355	32.45	35.556	39.492	0.385	1.611	1.856	2.546
25	271.368	278.697	278.992	286.652	0.461	8.403	9.487	12.456

6.0 CONCLUSIONS

6.1 Depth penetration experiments

The penetration depth studies provided information on the effect of soil moisture on fixative propagation through a soil matrix of mostly sandy soil. The chemical composition plays an important factor on soil penetration; only in one case was consistency a real factor on fixative performance. Calcium chloride has been known to effect soil permeability, so the penetration depth of the RoadMaster™ can be improved by increasing the application rate. The TAPAC GT performance was consistent with its known application; this fixative is intended to bind surface particles and restrict movement between the air and soil below the "crust". The Durasoil® fixative shows the maximum penetration depth, with the addition of water to the soil matrix prior to application improving penetration depth. The Dustbond® fluctuations require that thorough sampling of the soil surface to be stabilized be done in advance to know the moisture content. Additional testing, required to better explain the fluctuations observed, may include, but is not limited to, observing the soil structure under a microscope to identify the pore space and conducting a study to find the chemical reactions that are occurring between the soil and fixative, if any.

For all the fixatives, further cost analysis would have to be performed to determine the cost advantage of one versus another, especially when combining the results of the tests performed as part of this research study.

6.2 Wind tunnel experiments

Experiments were conducted using an open-loop, low-speed wind tunnel. The following sample matrices were exposed to wind speeds varying from 10 to 30 mph:

1. Hanford's SP soil with varying percent soil moisture by weight (2.7%, 5%, 10%, 15%, and 20%).
2. Hanford's SP soil sprayed with calculated dilution ratios of RoadMaster™ ($CaCl_2$), DustBond®, and DuraSoil® fixatives.
3. Hanford's SP soil with 2.7%, 5% and 20% soil moisture by weight mixed with 5%, 10%, 15% and 20% by weight of cerium oxide.

4. Hanford's SP soil at 2.7% moisture mixed with 5%, 10%, 15% and 20% by weight of cerium oxide and sprayed with two different dilution ratios of RoadMaster™ (5% and 10%).
5. Hanford's SP soil at 2.7% moisture mixed with 5%, 10%, 15% and 20% by weight of cerium oxide and sprayed with two different dilution ratios of DustBond® (0.5:1.0 and 7.0:1.0).
6. Hanford's SP soil with 2.7% moisture mixed with 5%, 10%, 15% and 20% by weight of cerium oxide and sprayed/poured with two different application rates of DuraSoil® (25% AR and 100% AR).

The following sections described the conclusions arrived during the performance of the above experiments.

6.2.1 Soil displacement due to wind forces

The results obtained for soil matrix # 1 [Hanford's SP soil with varying percent soil moisture by weight (2.7%, 5%, 10%, 15%, and 20%)] showed that:

1. As velocity increased, the amount of soil loss increased.
2. As percent moisture increased, the amount of soil loss decreased.
3. Initial percent moisture in the soil sample decreased by approximately 40% when exposed to the wind velocity.

It was concluded that an increase in velocity definitely played a role in the amount of soil displacement during the wind tunnel experiments. For Hanford's SP soil with 2.7% moisture, there was a 99% increase in soil loss as velocity was increased from 15 to 25 mph. For this case, an average of 0.5 grams of soil was lost at 15 mph but when velocity was increased to 25 mph, a total average of 157.5 grams of soil was lost. This was also true for Hanford soil containing 5% moisture by weight, there was no lost at 15 mph but there was as much as 111.0 grams of soil lost when velocity was increased to 25 mph.

In addition, the experimental results indicated that moisture content played a significant role in the ability of the soil to move when exposed to varying wind velocities. For a velocity of 20 mph, there was an average mass loss of 6.5 grams when soil moisture was 2.7% by weight. When the moisture content of the soil was almost quadrupled to 10% by weight, the amount

of mass displaced decreased to 0.135 grams. This was an approximately 98% difference (reduction) in mass displaced due to an almost 400% increase in soil moisture. If the moisture content in the soil is increased even further to 15% (almost 6 times the original moisture) for the same velocity (20 mph), the average amount of soil lost was only 0.03 grams. This is a 99% difference (reduction) in mass loss due to an almost a 600% increase in soil moisture. It was also observed from the experiments that there is no soil loss when the moisture content in the soil is 20% by weight; this is true at any velocity between 10 and 25 mph.

The results obtained for test matrix # 2 [Hanford's SP soil sprayed with three selected fixatives: RoadMaster™ ($CaCl_2$), DustBond® and DuraSoil® showed that:

1. Using manufacturer's recommended dilution and/or application rates, no soil loss was observed even at high velocities (25 mph – 30 mph).
2. Based on these preliminary results, the dilution ratios and/or application rates of these three fixatives were reduced as detailed in the previous section.
3. At these new dilution ratios and/or application rates, some soil movement was detected.
4. At these new dilution ratios and/or application rates, the results showed a definite improvement (when compared to baseline Hanford soil with 2.7% moisture) in the suppression of soil particles and airborne particles for all the velocities tested.

Initial experiments were conducted using vendor recommended application rates and dilution ratios for the three fixatives selected, but no soil movement was detected. Based on these preliminary results, new dilution ratios and/or application rates were calculated and applied to the soil.

Based on the calculated dilution and/or application rates, a small (reduced) amount of soil movement was obtained. In the case of the RoadMaster™ fixative, the highest amount of soil displaced was obtained at 30 mph where the soil loss was 4 grams, 2 grams, 1 gram, and 0 grams for $CaCl_2$ dilution ratios of 2.5%, 5%, 7.5%, and 10%, respectively. For this case, the amount of calcium chloride used for each dilution ratio was 0.69 ml, 1.38 ml, 2.07 ml, and 2.76 ml respectively. Based on the results obtained during these experiments, an average of only 10.0 grams (4.3%) of the soil was lost at a RoadMaster™ dilution rate of 2.5% (0.69 ml

of calcium chloride) and 2.0 grams (0.8%) of the soil at a dilution rate of 7.5% (2.07 ml of calcium chloride) during the entire experiment. This signified that only 10 grams of the soil was lost by using 0.69 ml of calcium chloride (dilution rate of 2.5%) vs. 2 grams of soil by using the 2.07 ml calcium chloride (dilution rate of 7.5%). The difference between these two dilution ratios (in terms of ml) is 66.7% more calcium chloride was used to capture an additional 8 grams of soil. When compared to the manufacturer's recommended 10.53 ml (38% calcium chloride) dilution rate, the difference between these two dilutions (in terms of ml) is 93% more calcium chloride was used to capture only 10 grams of additional soil. It can be concluded that there may be significant cost saving by reducing the dilution ratio of the calcium chloride to 2.5% or 5% since there was no significant increase in the amount of soil suppression by increasing the concentrations of calcium chloride from 2.5% to 38% (manufacturer recommended).

The dilution ratios for DustBond® were also modified from the manufacturer's recommended ratio of 7.0:1.0 (Water : DustBond®) to 0.5:1.0 and 1.0:1.0 (Water : DustBond®) ratios. Only a very small amount of soil displacement was detected at the lowest dilution ratio of 0.5:1.0 (Water : DustBond®) for a maximum velocity of 30 mph. Only an average of 3.0 grams (1.3% of the soil) was lost at the dilution ratio of 0.5:1.0 (Water : DustBond®). For the 7.0:1.0 (Water : DustBond®) dilution ratio, no soil displacement was observed at any velocity between 10 mph and 30 mph. An average of 0.0 grams (0%) of the soil was lost at this dilution ratio. The amount of water used for 7.0:1.0 (Water : DustBond®) and the 0.5:1.0 (Water : DustBond®) dilution ratios are 34.5 ml and 2.5 ml respectively. The amount of DustBond® was kept constant at 4.93 ml for all the experiments. The difference in the amount of water for these two dilution ratios is significant (92.7%), but the improvement in suppression performance is negligible (a difference of only 3 grams of soil). It can be concluded from the results that water a major contributor to the suppression of soil during these experiments. The application rates for the DuraSoil® fixative were also modified. For these experiments 25%, 50%, and 100% (manufacturer's recommended) concentration rates were used. For all velocities tested, very small amount of soil was lost. At the 25% application rate, only an average of 5.0 grams (2.1%) of the soil was lost, compared to a total average of 1.0 grams (0.4%) of soil loss at an application rate of 100%. The difference in the amount of DuraSoil® used for these two application rates, 25% and 100%, are 2.97 ml and 11.8 ml, respectively. This is a substantial amount considering that only 4 extra grams of soil is captured when the

manufacturer's recommended application rate was used. It is evident that cost savings can be achieved by reducing the application rate of the DuraSoil®

It can be concluded that the selected fixatives performed better than anticipated. In fact, manufacturer's recommended dilution ratios and/or application rates were only used for DustBond® (7.0:1.0) and DuraSoil® (100%), but no soil movement was detected for these applications. New dilution ratios and application rates were calculated and used during the execution of these wind tunnel experiments. The performance of the fixatives used in these experiments was comparable to the results obtained for Hanford's SP soil with higher percent moisture, mainly 10%, 15%, and 20%. For all these cases, very little soil (0-4 grams) was displaced.

The results obtained for soil matrices 3, 4, 5, and 6 (Hanford's SP soil with moistures of 2.7%, 5%, and 20% mixed with cerium oxide and matrices 4, 5, and 6 (Hanford's SP soil with initial 2.7% moisture, mixed with cerium oxide and sprayed/poured with fixatives) showed that:

1. The amount of mass displaced by wind forces, on the average, is higher when cerium oxide is added to the sample (when compared to matrices 1 and 2).
2. As moisture percent was increased from 2.7% to 20%, the amount of soil (including cerium oxide) displaced was decreased.
3. When fixatives were added to the soil/cerium oxide mixture, the soil displacement and PM10 generation were dramatically decreased.

Cerium oxide experiments also showed an increase in the amount of soil displaced and the amount of PM10 generated. For example, a maximum PM10 concentration of 279.095 mg/m^3 was obtained for Hanford's SP soil with 2.7% moisture at 20 mph. This is a 16% increased when compared to the same soil matrix (Hanford's SP soil with 2.7% moisture) but without cerium oxide simulant. Similar trends were observed for the other soil matrices tested.

6.2.2 PM10 concentration measurements

PM10 particle size measurements were collected for Hanford's SP soil with varying percent moisture (2.7% to 20% by weight) for velocities ranging from 10 to 25 mph. The largest

concentration recorded was 240.225 mg/m^3 and it was generated by the Hanford's SP soil with 2.7% moisture at a velocity of 25 mph. The amount of PM10 generated changed with decreasing wind velocity. For example, for the same soil moisture (2.7%) and a wind velocity of (15 mph), the average PM10 concentration decreased to 8.716 mg/m^3. It was also observed that as the soil moisture increased, the PM10 concentration decreased (Table 19). For example, for the same velocity of 15 mph but at 20% moisture, the PM10 concentration was only 0.103 mg/m^3.

PM10 concentrations were also measured for the three fixatives tested during this study. For this case, the DustBond® fixative showed better performance in suppressing the soil when compared with the DuraSoil® fixative. This can be seen by comparing the manufacturer's recommended dilution and/or application rates for these two fixatives. Also, manufacturer's recommended concentrations were used for DustBond® and DuraSoil® fixatives (7.0:1.0 and 100% dilution ratio and application rate respectively). A significant difference in the results was observed at these concentrations. For example, at 30 mph, the PM10 concentration for DustBond® was 0.400 mg/m^3 as compared to the results obtained for DuraSoil® (1.480 mg/m^3) at the same wind velocity (30 mph). All things being equal, 73% more PM10 concentration was detected when soil was sprayed with DuraSoil® for the same velocity (30 mph). Also when comparing DustBond® to the highest RoadMaster™ dilution ratio tested (10%), it can be seen from the data that DustBond® performed better than RoadMaster™ (0.400 mg/m^3 vs. 0.615 mg/m^3 at 30 mph). It was also observed from the data that the amount of PM10 generated increased as the velocity increased; this was true for all the three fixatives tested. It was also seen that the fixative performance was comparable with previous results obtained for Hanford's SP soil with 15% and 20% moisture content.

In the case of RoadMaster™, experiments showed that as velocity increased, the PM10 concentration also increased for all dilutions ratios tested. On the other hand, as the dilution ratio increased from 2.5% to 10%, the PM10 concentration decreased. At higher dilution ratios, the PM10 concentration was the lowest. This was observed for all velocities tested. This can be attributed to the amount of calcium chloride and water used to generated the desired dilution rations (Table 8). For example, to generate a dilution ratio of 10% RoadMaster™, 2.76 ml of calcium chloride and 7.77 ml of water was added to the soil sample. To generate a dilution ratio of 2.5% RoadMaster™, 0.69 ml calcium chloride and

9.84 ml of water was added to the soil sample. At a dilution ratio of 2.5% RoadMaster™ and 30 mph, the PM10 concentration was 3.097 mg/m^3 but when the dilution ratio was increased to 10%, the PM10 concentration was reduced to 0.615 mg/m^3. As the amount of calcium chloride was increased, the amount of PM10 generated decreased. Similar trends were observed in the case of DustBond® and Durasoil® fixatives although some fixatives had better performance. These trends are presented in Figures 26, 27 and 28, respectively.

In addition, in an effort to understand the dispersion characteristic of Pu powder and the ability of moisture and/or fixatives to suppress this contamination, a cerium oxide simulant was added to the soil samples. This simulant was mixed with Hanford's SP soil with varying percent moisture (2.7%, 5%, and 20%) and also mixed with Hanford's SP soil with initial 2.7% moisture and sprayed with the selected fixatives. Also, a comparison was made between Hanford's SP soil (2.7% moisture) with and without the addition of the cerium oxide simulant. Figure 29 compares the baseline case of 2.7% soil moisture for PM10 concentration without cerium oxide (Section 5.2.3) against 2.7% soil moisture mixed with cerium oxide at different concentrations (5%, 10%, 15% and 20%). It was noticed that for all cases, the PM10 concentrations were higher when cerium oxide was added. For example, at a velocity of 20 mph, the PM10 concentration was 233.390 mg/m^3 for soil without the simulant but when 5% cerium oxide concentration was added to the soil sample, the PM10 concentration increased to 279.095 mg/m^3. This translates to an increase in PM10 concentration of approximately 16%. If the cerium oxide concentration is increased even further to 20%, the PM10 concentration increases to an average of 289.955 mg/m^3. This signifies an approximate 19% increase when compared to the baseline of 2.7% soil moisture without cerium oxide.

It was also observed that as the cerium oxide concentration increased, the PM10 concentration increased. For example, at 5% soil moisture and 10% cerium oxide and at a velocity of 20 mph, the airborne concentration was 37.623 mg/m^3 but when the cerium oxide percentage increased to 20%, at the same wind speed (20 mph), the PM10 concentration increased to 72.568 mg/m^3 (Figure 31).

Again, an attempt was made to compare soil at 5% moisture with and without cerium oxide added to the soil sample (Figure 30). It was shown that for all cases, the PM10 concentration

was higher when cerium oxide was added to the soil sample. For example, at 5% soil moisture and at a velocity of 20 mph, the PM10 concentration was 0.385 mg/m^3, but when 5% cerium oxide was added to the sample, the PM10 concentration increased to 23.560 mg/m^3 for the same wind velocity of 20 mph. Similar trends were observed when the soil moisture was increased to 20%. For example, at 20% soil moisture and 10% cerium oxide and at a velocity of 20 mph, the airborne concentration was 0.754 mg/m^3 but when the cerium oxide concentration increased to 20% at the same wind speed (20 mph), the airborne particulate concentration increased to 0.573 mg/m^3 (Table 27).

PM10 concentration measurements were also recorded for RoadMaster™ with dilution ratios of 2.5% and 10% mixed with varying cerium oxide concentrations ranging from 5% to 20%. For both RoadMaster™ concentrations, it was observed (Table 30) that as the velocity increased, the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For example, at a RoadMaster™ concentration of 2.5% and at 20% cerium oxide, the PM10 concentration varied from 0.203 mg/m^3 to 9.123 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher RoadMaster™ concentration of 10% and a cerium oxide concentration of 20%. In this case, the PM10 concentration increased from 0.188 mg/m^3 to 5.245 mg/m^3 when the velocity was increased from 10 mph to 25 mph. At the same time, it was observed that the PM10 concentration decreased as the concentration of RoadMaster™ increased from 2.5% to 10%. Examining the previous example, the PM10 concentration decreased from 9.123 mg/m^3 to 5.245 mg/m^3 for the same velocity range of 25 mph. Similar trends were noticed for the other velocity ranges. Figures 32 and 33 compare the PM10 generation for the two RoadMaster™ concentrations (2.5% and 10%) with and without cerium oxide simulant. For both cases, it can be seen that there was a significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

PM10 concentration measurements were also recorded for two DustBond® dilution ratios of 0.5:1.0 and 7.0:1.0 (Water: DustBond®) mixed with varying cerium oxide concentrations ranging from 5% to 20%. For both DustBond® concentrations, it was observed (Table 32) that as the velocity increased, the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For example, at a DustBond® dilution ratio of 0.5:1.0 and a cerium oxide concentration of 20%, the PM10

concentration varied from 0.156 mg/m^3 to 7.891 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher DustBond® dilution ratio of 7.0:1.0 and the same cerium oxide concentration of 20%. In this case, the PM10 concentration increased from 0.099 mg/m^3 to 3.545 mg/m^3 when the velocity was increased from 10 mph to 25 mph. At the same time, it was shown that the PM10 concentration decreased as the dilution ratio of DustBond® increased from 0.5:1.0 to 7.0:1.0. Examining the previous example, the PM10 concentration decreased from 7.891 mg/m^3 to 3.545 mg/m^3 for the same velocity range of 25 mph. Similar trends were noticed for the other velocity ranges. PM10 generation for the two DustBond® dilution ratios (0.5:1.0 to 7.0:1.0) with and without cerium oxide simulant was also compared (Figures 34 and 35). For both cases, it can be seen that there was a significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

PM10 concentration measurements were also recorded for two DuraSoil® application ratios of 25% and 100% mixed with varying cerium oxide concentrations ranging from 5% to 20%. For both DuraSoil® application ratios, it was seen (Table 34) that as the velocity increased the PM concentration increased. This is true for all concentrations of cerium oxide simulant ranging from 5% to 20%. For example, at a DuraSoil® at 25% application ratio and a cerium oxide concentration of 20%, the PM10 concentration varied from 0.978 mg/m^3 to 286.652 mg/m^3 as the velocity increased from 10 mph to 25 mph. A similar trend was observed at a higher DuraSoil® application ratio of 100% and the same cerium oxide concentration of 20%. In this case the PM10 concentration increased from 0.654 mg/m^3 to 12.456 mg/m^3 when the velocity was increased from 10 mph to 25 mph. At the same time, it can be observed that the PM10 concentration decreased as the dilution ratio of DuraSoil® increased from 25% to 100%. Examining the previous example, the PM10 concentration decreased from 286.652 mg/m^3 to 12.456 mg/m^3 for the same velocity range of 25 mph. It is worth noticing here the increase in suppression capability of the DuraSoil® fixative when the application ratio was increased from 25% to 100% (full strength). Similar trends were noticed for the other velocity ranges. Figures 36 and 37 compare the PM10 generation for the two DuraSoil® application ratios (25% and 100%) with and without cerium oxide simulant. For both cases, it can be seen that there was a significant increase in the PM10 concentrations when cerium oxide was added to the soil/fixative mixture.

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