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Correlation of Penetration Resistance with Wind Erosion Resistance for Fugitive Dust Studies

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ABSTRACT

The correlation between surficial soil strength and wind erosion resistance was evaluated from testing performed at six agricultural sites in Pinal County, Arizona. Surficial soil strength was measured in-situ with a hand-held penetrometer. Wind erosion resistance was measured with a Portable In-Situ Wind Erosion Laboratory (PR-SWERL™). Agricultural sites were used because agricultural fields are suspected of playing a notable impact on air quality within the Phoenix area due to their susceptibility to the generation of fugitive dust (wind-induced soil erosion). A variety of hazards to human health and the environment are attributed to fugitive dust, including respiratory problems, obscured visibility, and compromised soil nutrient levels. Evaluation of the test results revealed a strong correlation between peak soil resistance measured by the penetrometer and the maximum concentration of air-entrained particulate matter equal to or less than 10 microns in diameter (PM_{10}) as measured by the PI-SWERL™. The average Pearson coefficient of 0.87 for this correlation provides a high degree of confidence in its applicability. These results suggest that penetrometer tests can serve as an effective and efficient tool for assessing the susceptibility of soil to generation of fugitive dust. This finding provides a practical method for predicting the potential for dust emissions from agricultural land and for assessment of land management practices.

INTRODUCTION

To establish a practical, effective, and efficient method of assessing the potential for generation of fugitive dust (wind-blown fine-grained soil), surficial soil strength using in-situ hand-held penetrometer test was compared to the maximum concentration of air-entrained particulate matter (PM_{10}) measured using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL™) at six undisturbed (fallow) soil sites in Pinal County, Arizona, USA. Fugitive dust (windblown erosion of fine soil particles) is a recognized hazard that can cause multiple adverse effects on human health and the environment. Fugitive dust presents health risks to humans and can create dangerous situations for vehicular traffic due to low visibility (Bhattachan et al. 2019). In addition, inhalation of fugitive dust can trigger asthma reactions and long-term exposure to fugitive dust may lead to lung disease, e.g., silicosis (Duniway et al. 2019).

Wind erosion is a natural process that plays a vital role in the cycling of nutrients and minerals within the soil ecosystem. As mountains and rocks undergo weathering and fragmentation, the wind acts as a key agent in transporting these particles to different locations. Although soil movement can be beneficial as a part of the natural cycling in the environment, it can also result in a reduction of soil resistance to erosion and loss of nutrients. In semi-arid regions where the soil is loose and dry and has minimal vegetation covers, the soil has a low resistance to wind erosion. When soil particles become airborne due to wind erosion, they are often referred to as fugitive dust. The air-entrained particulate matter equal to or less than 10 microns in diameter (PM_{10} measured in μg/m^3 or mg/m^3) can enter the body through the nose, mouth, and upper airways and cause irritation. The primary federal health standard for PM_{10} set by the US Environmental Protection Agency (USEPA) is 150 $\mu g/m^3$ over a one-day exposure (USEPA 2012). The US Occupational Safety and Health Administration (OSHA) has established a limitation for total airborne dust to not exceed 15 mg/m^3over workday hours. In many jurisdictions, excessive fugitive dust can lead to violation of these air quality regulations, resulting in monetary fines and other penalties. For instance, penalties for violations of the fugitive dust standard can reach up to $10,000/day in Maricopa County, Arizona, USA.

Nature has developed inherent mechanisms to resist wind erosion of soil, including natural self-crusting and vegetative cover. However, the low volume of rain precipitation in semi-arid regions can be a problem for development of these mechanisms. In addition, some human activities can reduce soil resistance to wind erosion including agricultural techniques like tilling and mono-cropping. A variety of interventions can be used to mitigate wind erosion of soil and the associated generation of fugitive dust. Mitigation strategies include increasing the soil resistance to fugitive dust formation, e.g., by wetting the soil, or reducing erosional wind velocities (e.g., with wind breaks). Results of this study indicate that surficial soil strength as measured in situ penetrometer tests can be used as an expedient tool to assess the susceptibility of natural undisturbed soil to the generation of fugitive dust.

SCOPE OF STUDY

Wind erosion resistance was measured using the PI-SWERL™ at six fallow agricultural fields in Pinal County, Arizona. The surficial soil strength for these six sites was measured in-situ using a hand-held penetrometer. The six sites were designated as Glenbar, Marana, Casa Grande, La Palma, Gilman, and Casa Grande 2 based on the US Department of Agriculture National Cooperative Soil Survey (USDA-NCSS) soil series names. Figure 1a shows the distribution of USDA-NCSS soil series in Pinal County and Figure 1b shows the locations where the tests used in this study were performed. These sites were selected depending on multiple factors, including the potential for self-crusting and soil carbonate content (as a percentage of the mass of solids). Previous studies show a high correlation between soil carbonate content and crust formation in soils from Pinal County (Scott et al. 2024). Pinal County was chosen for this study because the Arizona Department of Environmental Quality reports showed that most of the severe dust storms ("haboobs") that plague the region travel through Pinal County. Human activities like vehicular traffic and plowing can exacerbate dust generation and air particulate loads (PM_{10}). In particular, plowing agriculture fields leaves the soil particles weak and dry and can then exacerbate dust storm intensity. The dashed arrow in Figure 1b shows a typical dust storm path through Pinal County into the Phoenix metropolitan area (based on summer 2023 monsoon season). Table 1 provides more information about soil properties at each of the six sites.

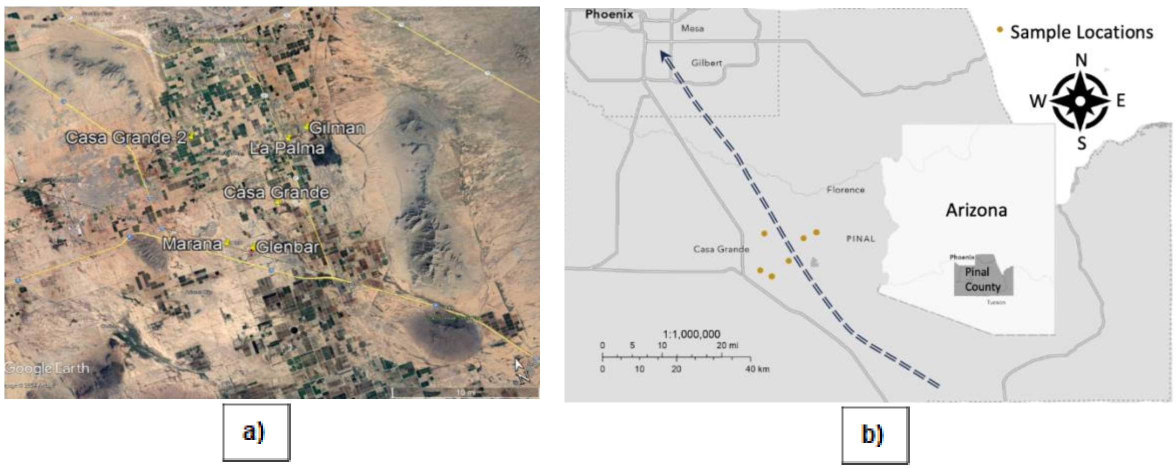


Figure 1. a) USDA-NCSS Soil Series within Pinal County, Arizona.
b) Dust Storm Path within Pinal County, Arizona.

Table 1. USDA-NCSS Soil Series Names and Properties

Soil name	Carbonate (%)	Clay (%)	pH	Organic Matter (%)
Glenbar	3.76	29.80	8.1	2.5
Marana	4.92	9.00	8.7	1.9
Casa Grande	4.62	16.60	8.2	1.6
La Palma	18.47	9.40	8.6	2.4
Gilman	3.01	7.60	8.3	1.8
Casa Grande.2	5.5	17.10	8.2	2.5

MATERIALS AND METHODS

The PI-SWERL™ (Dust Quant LLC, 2018) was used to evaluate the potential for dust formation by wind shear at six agricultural sites in Pinal County, Arizona, USA. The device, shown in Figure 2a, has a rotating flat annular blade in a cylindrical chamber closed at the top but open at the bottom. The chamber is approximately 23 cm (9 inch) in diameter and the blade is positioned approximately 6.4 cm (2.5 inch) above the base of the device (i.e., above the soil surface when deployed). The motorized annular blade generates increasing levels of wind shear by increasing the revolutions per minute (rpm) of the blade from 0 to 6000 rpm, corresponding to wind speeds of 0 to 18 m/s (Etyemezian et al, 2007). The device measures the PM_{10} concentration in the chamber continuously as the blade rotates.

In this study, a stepwise increase in rpm, starting from 0 to 200 rpm to 2000 rpm and subsequently in 1000 rpm increments to 6000 rpm were implemented to capture PM_{10} concentrations at discrete wind speeds, enabling the determination of threshold velocity for incipient particle motion. Blade rpm (wind speed) was progressively increased until either fugitive dust was observed or the test reached the maximum rpm. During each stepwise increase in blade rpm PM_{10} concentrations in the chamber were measured using a nephelometer-style dust monitor. In some cases, this process left an annular imprint on the soil surface at the end of the test (Figure. 2b). The resulting PM10 versus wind speed plot generated in this manner provides an assessment of the soil wind erosion potential. Previous studies have shown a strong correlation between these PI-SWERL^{TM} measurements and large-scale portable wind tunnel field data, confirming the reliability of this method in field applications (Etyemezian et al. 2007; Sweeney et al. 2008).

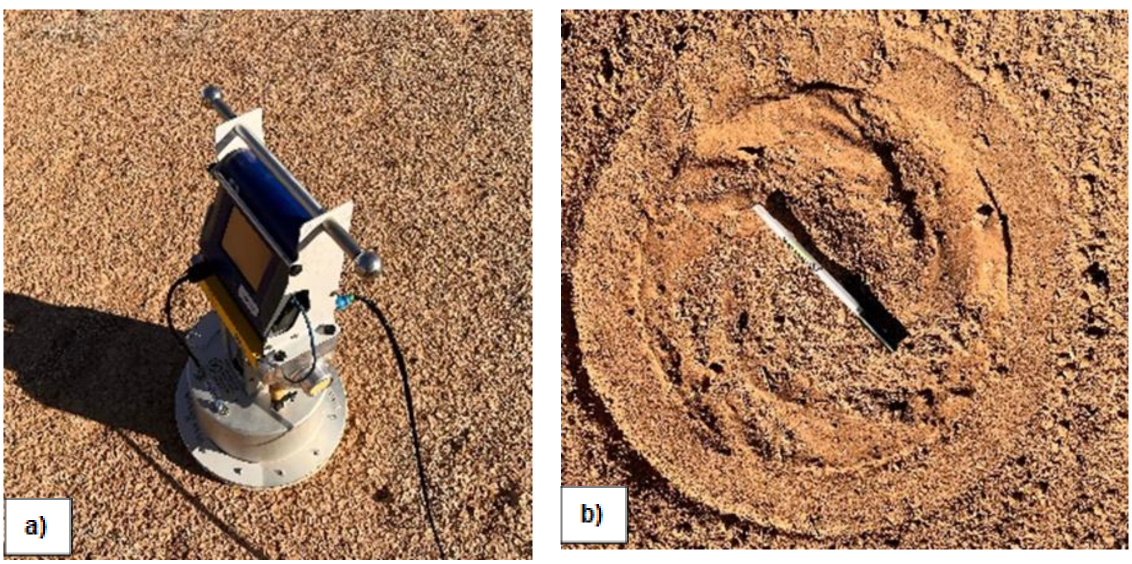


Figure 2. a) PI-SWERL^{TM} seated on soil surface; b) Soil surface after testing

The PI-SWERL™ device, while effective, is expensive, bulky, and requires significant time for setup and testing. Consequently, in addition to using the PI-SWERL™, a hand-held "pocket penetrometer" was employed to assess soil surface strength. Penetrometer readings have been established in the literature as a reliable method for estimating unconfined compressive strength (UCS) of soil (Mousavi et al., 2021). Mousavi et al. (2021) demonstrated a strong correlation ($R^2 = 0.98$) between pocket penetrometer readings and UCS values in fine-grained soils, demonstrating its reliability as a cost-effective method for UCS estimation.

A Humboldt soil pocket penetrometer (model H-4195), shown in Figure 3, was used to obtain field measurements of soil penetration resistance in tons per square foot (tsf) or kg/cm². The pocket penetrometer features a spring-loaded stainless-steel piston, 0.25 inches (6.35 mm) in diameter, which retracts as it is pressed into the soil surface. When the piston penetrates the soil, the peak penetration resistance (in tsf) is recorded by a black plastic band on the device. Penetration resistance is subsequently converted to UCS (in kPa) in accordance with the manufacturer's recommendations. Three penetrometer tests were conducted at each PI-SWERL™ location to evaluate the hypothesis that wind erosion potential was correlated to surficial soil strength.

a) Weak Soil Crust b) Strong Soil Crust

Figure 3. Pocket Penetrometer and representative test soil

RESULTS & DISCUSSION

Figure 4 shows the results of PI-SWERL™ testing at the six undisturbed soil sites in Pinal County. In this figure, PM_{10} emissions (mg/m^3) are plotted against the equivalent wind velocity (m/s) of the rotating blade. The vertical arrows indicate the locations of the six equivalent wind speeds of 1, 6.5, 9, 12, 14.5, and 16.5 m/s used in the testing program. Figure 5 presents the results of penetrometer tests conducted at the six different sites in Pinal County. The measured values, reported in tons per square foot, indicate the in-situ soil strength at each location. Table 2 summarizes the test data, including the maximum PM_{10} concentration (mg/m^3) at each wind velocity and the average crust strength (converted to kPa) from the three penetrometer tests conducted at each location. The results include standard deviation, which illustrates the variability of the measurements at each site.

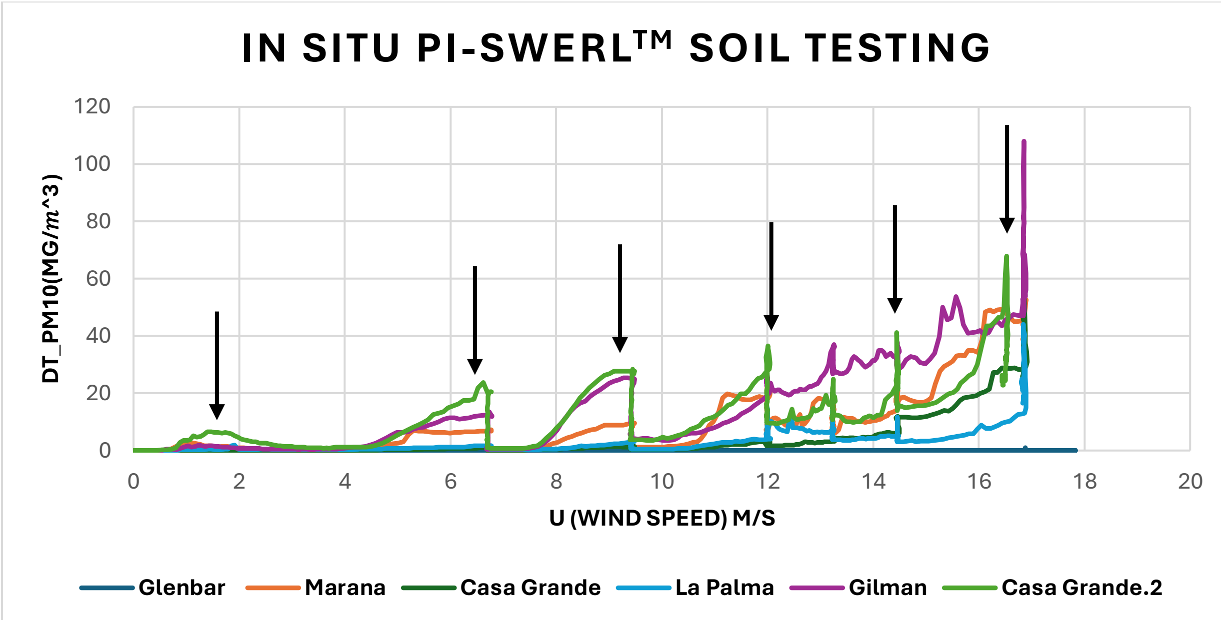


Figure 4. Pinal County PI-SWERL™ Results. (The vertical arrows indicate the locations of the six equivalent wind speeds).

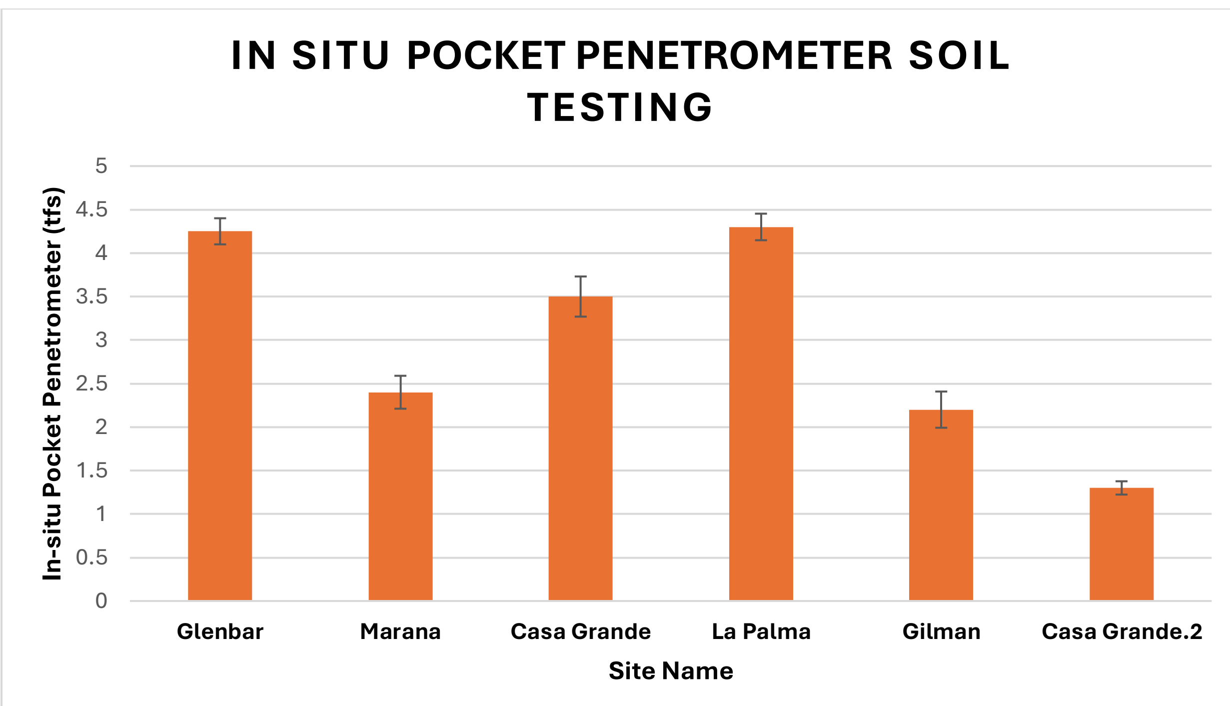


Figure 5. In-situ Pocket Penetrometer results across the six study sites. (The black bars show the standard deviation from three tests).

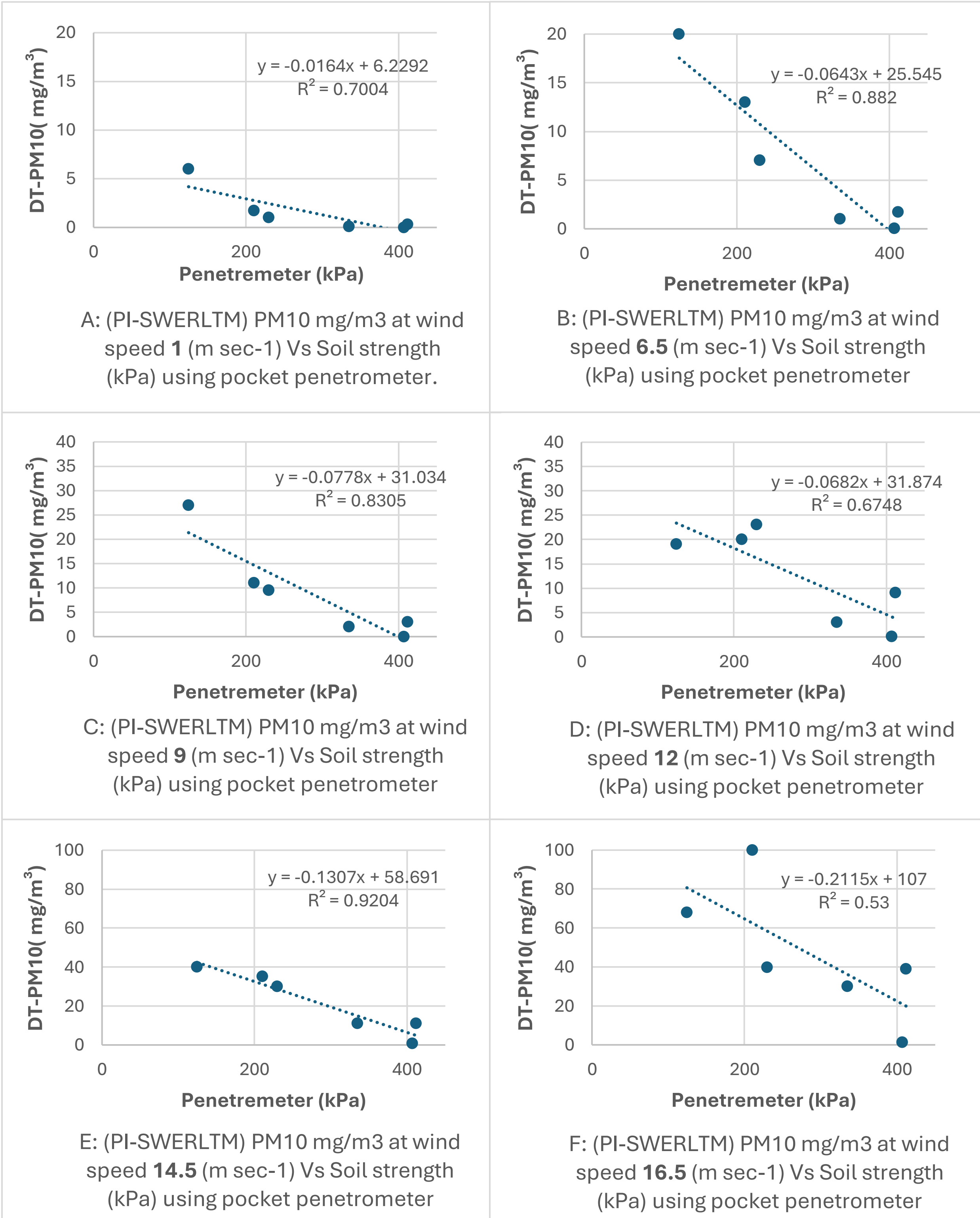
Table 2. PI-SWERL™ and Penetrometer data for the six Pinal County sites

Site Name	Average Penetrometer Strength (kPa)	Max PM_{10} Concentration (mg/m^3) at Velocity of:					
		1 m/s	6.5 m/s	9 m/s	12 m/s	14.5 m/s	16.5 m/s
Glenbar	406.98	0	0	0	0	0.5	1.5
Marana	229.82	1	7	9.5	23	30	40
Casa Grande	335.16	0.1	1	2	3	11	30
La Palma	411.77	0.3	1.7	3	9	11	39
Gilman	210.67	1.7	13	11	20	35	100
Casa Grande.2	124.48	6	20	27	19	40	68

Figure 6 presents plots of PM_{10} concentration versus penetrometer resistance at the six test sites for each of the six equivalent wind velocities used in the PI-SWERL™ testing. The statistical analysis of penetrometer strength versus PM_{10} data in Figure 6 yielded an average Pearson correlation coefficient, r, of 0.87, ranging between 0.73 and 0.96, indicating a strong positive linear relationship overall. Table 3 presents both the Pearson correlation coefficient (r) and the coefficient of determination (R^2) at each equivalent wind speed

Table 3. Strength of correlation between Pocket Penetrometer strength and PM_{10} reading from PI-SWERL™ testing as a function of equivalent wind velocity

Equivalent Wind Velocity	Coefficient of Determination (R^2)	Pearson Correlation Coefficient (r)
1.0 m/s	0.70	0.84
6.5 m/s	0.88	0.94
9.0 m/s	0.83	0.91
12.0 m/s	0.68	0.83
14.5 m/s	0.92	0.96
16.5 m/ s	0.53	0.73



A: (PI-SWERLTM) PM10 mg/m3 at wind speed **1** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer.

B: (PI-SWERLTM) PM10 mg/m3 at wind speed **6.5** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer

C: (PI-SWERLTM) PM10 mg/m3 at wind speed **9** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer

D: (PI-SWERLTM) PM10 mg/m3 at wind speed **12** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer

E: (PI-SWERLTM) PM10 mg/m3 at wind speed **14.5** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer

F: (PI-SWERLTM) PM10 mg/m3 at wind speed **16.5** (m sec-1) Vs Soil strength (kPa) using pocket penetrometer

Figure 6. In-Situ Penetration Resistance versus PM_{10} Concentration at Six Equivalent Wind Velocities

From Table 3 and Figure 6 it can be seen that, at moderate wind speeds, e.g., at 6.5 m/s ($r = 0.94$, $R^2 = 0.88$) and 14.5 m/s ($r = 0.96$, $R^2 = 0.92$), the correlation was particularly strong, suggesting that soil strength significantly influences PM_{10} emissions under these conditions. This is likely due to the ability of stronger soils to resist wind erosion, thereby reducing PM_{10} emissions. Similarly, at 9.0 m/s ($r = 0.91$, $R^2 = 0.83$), the relationship remained robust, reinforcing the impact of soil mechanical properties on dust generation. However, at lower wind speeds (1.0 m/s, $r = 0.84$, $R^2 = 0.70$) and at the highest wind speed (16.5 m/s, $r = 0.73$, $R^2 = 0.53$), the correlation weakened (though may still be considered to be relatively strong). The reduced correlation at 1.0 m/s suggests that wind-induced PM_{10} emissions are less dependent on soil strength at low wind speeds, possibly because the wind energy is insufficient to mobilize particles regardless of soil resistance. Conversely, at 16.5 m/s, the correlation decline may be attributed to the overwhelming influence of wind energy, where even strong soils may experience surface particle detachment due to turbulent forces, reducing the relative impact of soil strength on PM_{10} emissions.

CONCLUSION

Statistical analysis of results of Pocket Penetrometer and PI-SWERL™ testing at six agricultural soil sites in Pinal County, Arizona, USA, supports the hypothesis that susceptibility to fugitive dust generation is correlated to surficial soil strength. The correlations between PM_{10} emissions (measured with the PI-SWERL™) and the in-situ pocket penetrometer on undisturbed soil were strong, with R^2 values ranging from 0.53 to 0.92 for the six velocities used in the testing program. This field correlation study provided an average of a Pearson correlation coefficient equal to 0.87. These results suggest that the in-situ pocket penetrometer test could serve as a practical and reliable alternative method when logistical challenges exist for more sophisticated testing (e.g., PI-SWERL™ or portable wind tunnel testing). While additional testing at a wider range of sites on both undisturbed and disturbed soils is needed, these results suggest that pocket penetrometer testing provides an expedient method for evaluating the susceptibility of a soil to wind-induced soil erosion, i.e., to generation of fugitive dust.

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