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Air jet setup for evaluating wind erosion resistance of soil

Configuration du jet d'air pour évaluer la résistance à l'érosion éolienne du sol

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ABSTRACT: A portable air jet wind erosion resistance test method has been developed to determine threshold friction velocity (TFV), the wind velocity at which surficial soil particles become detached and entrained in the air stream. While wind tunnel testing is sometimes used to evaluate the TFV of soil, wind tunnels often do not generate sufficient wind velocity to determine the TFV of a cemented soil and cannot be used in situ. To overcome these limitations, a portable air jet test method was developed. In this method, a horizontal air jet with a 6.35-mm nozzle diameter is positioned parallel to the soil surface. Air velocity is measured with an anemometer positioned at the discharge from the nozzle. To test the viability of this method, TFVs measured on control specimens in the laboratory using the air jet method were compared to TFVs measured using a boundary layer wind tunnel. The TFV for air jet testing of a poorly graded fine sand and of a silty sand were from 14-23% less, on average, than the wind tunnel TFV, suggesting a correction factor may be required to correlate results. This correction factor is worth pursuing as the air jet is capable of higher velocities than most boundary layer wind tunnels and can be used in both the laboratory and the field.

RÉSUMÉ : Une méthode portable d'essai de résistance à l'érosion par le vent à jet d'air a été développée pour déterminer la vitesse de frottement seuil (TFV), la vitesse du vent à laquelle les particules de sol superficielles se détachent et sont entraînées dans le flux d'air. Alors que les essais en soufflerie sont parfois utilisés pour évaluer le TFV du sol, les souffleries ne génèrent souvent pas une vitesse du vent suffisante pour déterminer le TFV d'un sol cimenté et ne peuvent pas être utilisées in situ. Pour surmonter ces limitations, une méthode d'essai au jet d'air portable a été développée. Dans cette méthode, un jet d'air horizontal avec un diamètre de buse de 6,35 mm est positionné parallèlement à la surface du sol. La vitesse de l'air est mesurée à l'aide d'un anémomètre placé à la sortie de la buse. Pour tester la viabilité de cette méthode, les TFV mesurés sur des échantillons témoins en laboratoire en utilisant la méthode du jet d'air ont été comparés aux TFV mesurés en utilisant une soufflerie à couche limite. Le TFV pour les tests au jet d'air d'un sable fin mal classé et d'un sable limoneux était de 14 à 23 % inférieur, en moyenne, à celui du TFV en soufflerie, ce qui suggère qu'un facteur de correction peut être nécessaire pour corréler les résultats. Ce facteur de correction mérite d'être poursuivi car le jet d'air est capable de vitesses plus élevées que la plupart des souffleries à couche limite et peut être utilisé à la fois en laboratoire ou sur le terrain.

KEYWORDS: threshold friction velocity, horizontal free air jet, fugitive dust control

1 INTRODUCTION

An air jet system has been developed as a simple method to measure the potential for detachment of soil particles from the ground surface due to wind (i.e., wind erosion susceptibility). This system was designed to provide a simple method of rapid assessment of wind erosion resistance in situ, facilitating better spatial representation of a site, and to overcome some of the limitations of wind erosion potential tests, e.g., limitations on the achievable velocity. This test method uses a pressurized air jet system to measure threshold friction velocity (TFV), the wind velocity at which surficial soil particles become detached and entrained in the air stream. The TFV from laboratory wind tunnel testing on control specimens was compared to TFV measured using the air jet system to evaluate the viability of the setup.

Air pollution due to wind entrainment of fine grained soil, sometimes referred to as fugitive dust, causes significant adverse effects to human health and the environment (Dockery et al. 1993). As arid and semi-arid environments get drier, dust will only become a bigger problem (Duniway et al. 2019). Fugitive dust from recreational or earth movement activities and natural wind erosion of soil both contribute to dust pollution.

Mitigation of fugitive dust through creation of a biocemented soil crust using enzyme induced carbonate precipitation (EICP) or microbially induced carbonate precipitation (MICP) has attracted recent research interest (Arab et al. 2021; Fattahi et al. 2020; Hamdan and Kavazanjian 2016; Krajewska 2018; Song et al. 2020; Tian et al. 2018; Zomorodian et al. 2019). Laboratory testing has shown that EICP can mitigate dust pollution through formation of a soil crust. However, moving this technology from the laboratory to the field has several challenges, including evaluation of the TFV after deployment.

Surface conditions such as soil texture, moisture content, surface roughness, vegetation and rock cover, and presence of a crust significantly affect the TFV of a surficial soil. The traditional method of measuring the TFV of a soil relies upon wind tunnel testing. However, wind tunnel testing is limited by the difficulty of moving the test setup and the inability to generate a velocity high enough to measure the TFV even in weakly crusted soils (Hamdan and Kavazanjian 2016; Marticorena et al. 1997; Nickling 1984). Techniques such as introducing disturbances (e.g., upstream roughness elements or saltating particles in the air flow in wind tunnels (Rice et al. 1996)) and damaging the crust with vibration or other means have been used to compare the durability of control and crusted soil specimens and to optimize treatments for dust mitigation potential (Fattahi et al. 2020; Song et al. 2020). These disturbance methods may be more representative of the chaotic interaction between the wind shear forces and the natural terrain (Tieleman 1992). However, the inclusion of such external factors complicates the computation of the TFV. For instance, use of an air rifle to measure TFV supplemented with torvane shear, pocket penetrometer, and surface roughness measurements found soils with erosion-resistant crusts underestimated the TFV unless a surface roughness correction factor was applied (Li et al. 2010).

The air jet system tested in this paper was developed to measure the TFV of biocemented soil crusts (i.e., crusts created with EICP and MICP for fugitive dust control) in the field and at velocities greater than achievable, in most wind tunnels.

2 BACKGROUND

2.1 *Wind Erosion of Soil*

Wind erosion of soils initiates at the creep stage with soil particles rolling along the bed, followed by saltation where particles bounce and impact the surface, and finally suspension where particles are suspended into the air for some time before being deposited. The forces required to initiate particle movement by wind can be expressed simply as the wind-induced drag and lift forces. Individual soil particles resist erosion through cohesion, interlocking with adjacent particles, and gravity (Shao and Lu 2000). A soil surface's ability to resist erosion is therefore dependent on the characteristics of the wind, the assemblage of soil particles, and the characteristics of the soil surface.

When wind blows across a soil surface it creates a viscous sublayer (Kadivar et al. 2021). In this sublayer, the airstream flows laminarly until it encounters roughness elements on the ground surface creating a roughness sublayer of chaotic and random airflow. Roughness protects the surface by creating physical barriers but also introduces turbulence into the flow that increases erosion. Roughness can influence the wind profile on both a small-scale (e.g., with ground cover) and on a large-scale (e.g., with trees and buildings).

Surface conditions significantly affect the TFV and include many factors such as soil texture, moisture content, surface roughness, surface cover, and presence of crusting. Elements that contribute to roughness are defined by a roughness length (z_0) which considers variations in the terrain height along a defined horizontal distance. For example, cities tend to have numerous large obstacles and result in much larger roughness lengths than deserts (World Meteorological Organization 2008). Surface roughness is an important factor when measuring the TFV and factors in other surface modifications, such as crusting, which is known to roughen a soil surface (Marticorena et al. 1997).

The wind erosion resistance of a soil surface is typically quantified by the TFV. Larger cohesionless particle sizes have a higher TFV than smaller particles that have less mass (Garrels 1951). However, fine-grained soil particles have enhanced erosion resistance due to interparticle locking and cohesion. This cohesion is due to the ionic charges of the particle surface and cations in the pore water adsorbed to the particle surface, firmly sticking them together. Thus, the most wind erosion susceptible particle size falls within the find sand to silt size range, e.g., around 0.18-mm, as shown in Fig. 1.

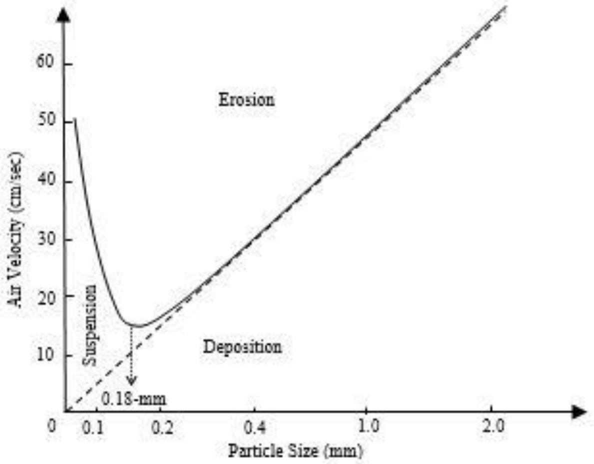

Figure 1. Threshold friction velocity required to initiate wind erosion of soil based on particle size.

Formation of any type of soil crust increases the TFV of a soil surface. Natural crusts include living biological soil crust or non-living layers of desert pavement. However, natural crust formation takes several years, or longer, before it can provide significant erosion resistance, and many natural crusts are easily disturbed. Once disturbed, the erosion resistance of soil crusts is significantly reduced (Belnap and Gillette 1998).

A common short-term dust mitigation method in arid and semi-arid regions is to repeatedly spray the surface with water, maintaining an elevated soil moisture content. Moisture increases the TFV until evaporation dries the soil out again. If the soil contains a significant fraction of fines, then there is potential for a thin aggregated soil crust to form as the surface dries. Increasing the thickness and strength of the crusted layer correlates to increased resistance to wind shear and particle impacts (Goossens 2004). Although the measurement of TFV typically uses laminar flow, the actual wind profile in the field is turbulent, with horizontal and vertical flows that interact with the surface.

2.2 *Fluid Mechanics of an Air Jet*

The wind sublayer induced by an air jet at the surface can be idealized into a horizontal two-dimensional air stream. The velocity distribution of a two-dimensional horizontal free air jet is shown in Fig. 2.

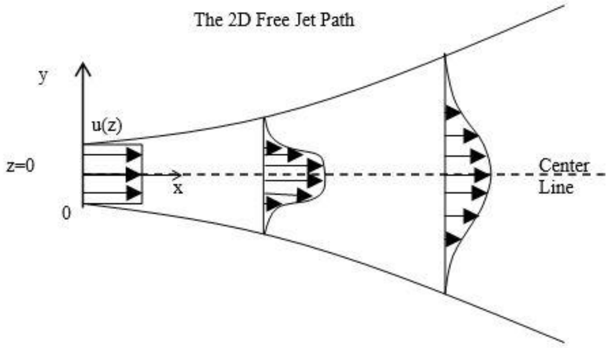

Figure 2. Illustration of the development of the flow field of a two-dimensional free jet.

The velocity profile spreads out with increasing distance away from the nozzle. A maximum velocity occurs at the nozzle discharge and the velocity remains highest along the centerline of the nozzle (Crenshaw 1966). This maximum velocity decreases as the flow spreads out over the surface, as shown in Fig 2.

The free air jet illustrated in Fig 2, when interacting with a smooth and rigid surface, generates a smooth horizontal flow. In this region, the friction velocity is related to wind speed using Eq. 1 (Pi and Sharratt 2019):

$$u(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{1}$$

where $u(z)$ (m/s) is wind speed at measurement height z (m), κ is von Karman's constant (set at 0.4), u_* (m/s) is friction velocity, and z_0 (m) is the roughness length. Equation 1 shows that for a constant wind velocity, an increase in roughness increases the friction velocity. The TFV is defined as the minimum friction velocity required to initiate continuous particle movement at a soil surface.

3 SCOPE OF THIS STUDY

The objective of this study was to develop a simple air jet system that could be employed in the laboratory or field for measuring the threshold friction velocity (TFV) of soil surfaces. A secondary objective was to develop a system to measure TFV at higher velocities than possible in a typical boundary layer wind tunnel. Testing was conducted on a poorly graded clean sand and a well graded silty sand. TFV measured using a free air jet setup developed for this project was compared to testing conducted in a boundary layer wind tunnel and with a portable in-situ wind erosion laboratory (PI-SWERL) device (Etyemezian et al. 2007).

Threshold friction velocity with the air jet system was measured by observing the soil particle flux from the soil specimen surface and noting the velocity at which particle erosion became continuous. Velocity was measured with an anemometer placed directly after the jet nozzle and the velocity at which particle erosion became continuous was designated the air jet erosion value (AJEV). Testing in this study was limited to untreated control specimens to evaluate the relationship between the AJEV and the TFV measured using the wind tunnel and PI-SWERL device. However, the air jet developed in this study can measure higher TFVs than either the wind tunnel or PI-SWERL device and the next steps in this research will be to use the air jet to evaluate the TFV of specimens with a soil crust created using EICP and MICP.

4 MATERIALS AND METHODS

4.1 *Test Soils and Specimen Preparation*

Testing was performed on a clean fine silica sand purchased from a materials supplier, termed F-60 sand, and a silty sand soil from Phoenix, Arizona, USA, termed AZSM. Fig. 3 presents the particle size distribution of the two soils and Table 1 contains the soil classification according to the Unified Soil Classification System (USCS) along with mean particle size.

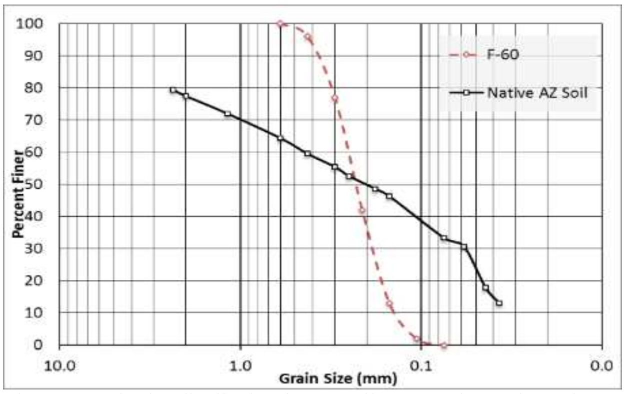

Figure 3. Grain size distribution for test soils: AZSM is a native Arizona, USA silty sand, and F60 is a clean poorly graded silica sand.

The USCS classification of the F60 silica sand was a poorly graded sand (SP) and the AZSM classified as a well graded silty sand (SM). Based upon particle size, both of these soils have a significant fraction of highly erodible material in the range of particle size most susceptible to wind erosion (Garrels 1951).

Table 1 also provides the test specimen relative denisty and a surface roughness factor as approximated by a subjective visual comparison to similar surfaces (Etyemezian et al. 2014). The specimen container used in the testing program was a 38-mm deep by 228-mm diameter aluminum pan. Specimens were prepared by loosely pouring dry soil into the test container in two lifts, tapping lightly fifteen times around the sides of the container after each lift, then leveling off the soil surface to be even with the edge of the container. The prepared specimens were in a very loose state for both soil types, as indicated by the relative density values in Table 1.

Table 1. Soil name, USCS classification, specimen relative density, and surface roughness for wind erosion test soils

Soil Name	*USCS Classification*	*Mean size* (D_{50} – *mm*)	*Specimen relative density* (D_R - *%*)	*Specimen surface roughness* (α)
F60	SP	0.23	3	0.97
AZSM	SM	0.20	5	0.92

4.2 *Wind Tunnel Experiment*

The Arizona State University Wind Tunnel (ASUWIT) is an open circuit boundary layer wind tunnel with a 13.7-m long, 0.7-m high, and 1.2-m wide working section to simulate laminar flow. The ASUWIT operates under ambient temperature and pressure conditions and is capable of wind speeds of 30 m/sec (Williams 2013). The floor of the wind tunnel was covered with sandpaper to provide a similar roughness to the soil specimens. Each specimen was inserted into a circular cut-out in the bed of the wind tunnel such that the soil surface was flush with the floor of the wind tunnel and was positioned along the centerline of the working section. Wind tunnel experiments were conducted in triplicate on untreated control specimens.

To begin a test run, the wind tunnel velocity was started at an idle wind speed of 2.0-3.5 m/s and then increased to and held at 5 m/s for 1-minute. This process was repeated for wind velocities of 10, 15, 20, and then 24 m/s (the safety limit set by the wind tunnel technician during testing). Soil particle detachment was monitored by visual observation under controlled lighting. To obtain the mass losses, the samples were weighed at the beginning and at the end of each test run.

4.3 *Air Jet Testing*

An in-line air pressurized system with a 6.35-mm diameter jet nozzle and a maximum pressure of 690 kPa was set so the nozzle was resting just above the surface of the specimen and the air stream was parallel to the surface. The velocity of the air jet was measured with an anemometer at both the nozzle discharge and at the far end of the specimen before and after each test reading, as shown in Fig 4.

Figure 4. a) Air jet test setup set at the edge of a F60 specimen and b) taking a reading at the nozzle of the pressurized air jet with an anemometer.

The velocity induced by the air jet setup was correlated to the applied air pressure using the anemometer readings. A set of typical anemometer measurements are plotted in Fig 5. This data shows the dissipation of the wind shear as the air jet stream interacts with the surface of the specimen. The AJEV was taken as the reading from the anemometer at the nozzle discharge when continuous detachment was observed in the specimen. The AJEV and the measured velocity at the far end of the specimen set the range across the specimen surface. However, the AJEV was used for comparison with the wind tunnel TFV in this study.

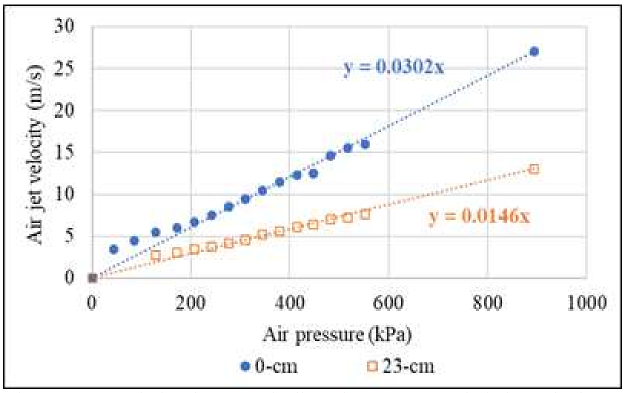

Figure 5. Correlation between in-line air pressure and air jet velocity at the nozzle (0-cm) and the end of the specimen (23-cm).

Air jet testing consisted of holding the jet velocity for a sustained velocity at 3, 5, 7, 8, 10, 12, 15, 18, 19, 20, 22, 24, and 25 m/s measured at the nozzle discharge. The air jet erosion velocity (AJEV) was defined as the threshold nozzle velocity at which the soil was continuously eroded by the air jet stream in a 1-minute time interval. Each specimen was weighed before each velocity increase to track mass loss over the test runs. However, the primary purpose of the air jet setup was to establish a practical alternative to wind tunnel testing for measuring the TFV.

Fig 6. shows images of an F60 sand specimen and an AZSM specimen at the conclusion of testing with the air jet. Each specimen eroded in a distribution similar to the free jet path distribution of the two-dimensional flow path.

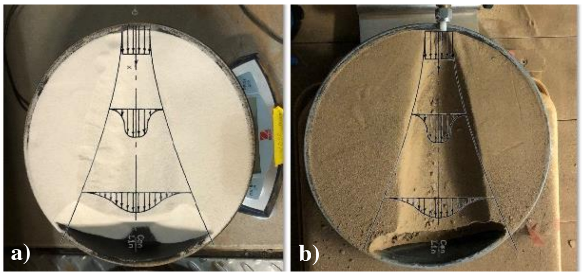

Figure 6. Air jet tested soil control specimens with the free jet stream distribution for a 2D horizontal flow plotted on top of each specimen for a) F60 sand (SP) and b) AZSM silty sand.

In the roughness sublayer near the ground surface, viscous effects dominate, so the wind-induced shear stress is dependent on the flow velocity and density of the fluid (air). Evaluating this induced shear stress combines the effects of the viscosity of the fluid with turbulence. The AJEV should be adopted as the index property for soil wind erodibility in this test when used for comparison with the TFV of other test methods.

4.4 *Portable In-Situ Wind Erosion Laboratory (PI-SWERL) Testing*

The PI-SWERL is a portable device produced by Dust Quant LLC. of Henderson, Nevada, USA, for the explicit purpose of measuring the dust flux from a surface subject to wind shear (Etyemezian et al. 2007). The PI-SWERL affixes an open-bottomed chamber with an area of 0.035m^2 over the soil surface. A wind shear is then applied to the soil surface via a rotating annular blade within the chamber. Sensors within the chamber detect larger saltating particles while an attached PM$_{10}$ sensor measures the flux of smaller dust particles.

The software associated with the PI-SWERL calculates friction velocity (u_*), using Eq 2:

$$u_* = C_1 \alpha^4 (RPM)^{\frac{C_2}{\alpha}} \tag{2}$$

where C_1 and C_2 are constants, the value of α depends on the surface roughness, and RPM is rotating speed of the annular blade in rotations per minute (Dust Quant LLC. 2018; Etyemezian et al. 2014). The threshold value of (u_{*t}) measured using the PI-SWERL has been found to show good agreement with measured values of TFV from wind tunnel tests (Etyemezian et al. 2007; Sweeney et al. 2008).

5 RESULTS

Fig 7 presents the results of the air jet testing on for both soil types F60 and AZSM specimens plotted in terms of wind velocity (including AJEV) and friction velocity evaluated using Eq 1. The wind speed measurement height (z) was set up to 1-m with roughness lengths of $z_0 =$ 0.97 for clean sand and 0.92 for silty sand.

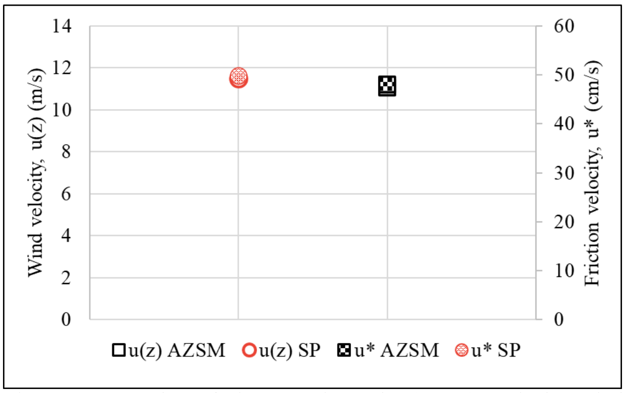

Figure 7. Mean values of Air Jet Erosion Value (AJEV), equivalent wind speed, and threshold friction velocity for the AZSM silty sand and the F60 clean sand.

PI-SWERL tests were conducted in the laboratory on both F60 and AZSM specimens using the same types of specimens evaluated in the air jet and wind tunnel tests. The results from PI-SWERL testing are presented in Fig 8 where the threshold friction velocity was assigned to the point where the PM$_{10}$ curve started to depart from the horizontal axis and was calculated using Eq 2.

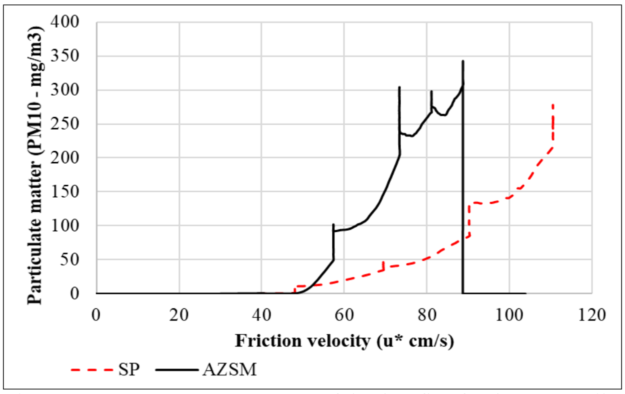

Figure 8. PI-SWERL measurements of the dust flux for the AZSM silty sand and F60 clean sand.

TFV values from wind tunnel tests conducted on F60 and AZSM specimens are presented in Figure 9. This figure compares these values with the TFV from the PI-SWERL tests and the AJEV. The calculated TFV values for each test method are also presented in Table 2.

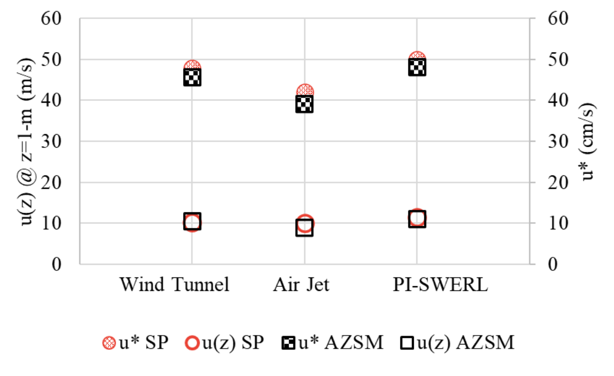

Figure 9. Comparison of wind tunnel, air jet, and PI-SWERL measurement of threshold friction velocity for AZSM silty sand and F60 clean sand (SP).

Table 2. Measured air velocities among the three wind erosion test methods for both soil specimen types.

		Threshold friction velocity (cm/s)		
Soil Name	*USCS Classification*	*ASUWIT*	*AJEV*	*PI-SWERL*
F60	SP	48	42	*50*
AZSM	SM	46	39	48

While the TFV results were consistent with respect to soil type and test method, with both the wind tunnel and PI-SWERL measuring TFV values of 50 ± 2 cm/s (11 m/s); the measured AJEV underestimated the TFV, signifying that including a correction factor (e.g., roughness length) improves the calculation of the friction velocity.

6 CONCLUSION

There is growing interest in developing treatments to mitigate wind erosion of soil by increasing the threshold friction velocity (TFV) of the soil surface, including the formation of biocemented soil crusts using enzyme induced carbonate precipitation (EICP) and microbially induced carbonate precipitation (MICP) treatments. This increases the need to develop simple methods to evaluate the wind erosion resistance or TFV of a soil surface with a crust. To address this need, a simple air jet test that can be used in the laboratory or field measurement has been developed. Wind tunnel and PI-SWERL testing performed in parallel to air jet tests on untreated soil specimens show that the air jet test underestimates the threshold friction velocity (TFV), the wind velocity at which the soil starts to erode, for both soil types (a poorly graded fine sand and a well graded silty sand). One factor of this discrepancy is exclusion of the roughness length, as an increase in which also increases the friction velocity value.

The air jet system has several advantages that warrant additional testing to develop a correction factor to better correlate between an air jet erosion value (AJEV) and the TFV, where TFV values were measured with wind tunnel and PI-SWERL testing. The air jet setup provides a means for quick measurement of an AJEV within 2-cm/s of the measured TFV, with quick and easy set up and each test completed in less than ten minutes. The air jet setup also offers the potential for testing at higher velocities than possible in wind tunnel tests. Therefore, additional research is taking place to resolve the discrepancy between the air jet results and other wind friction velocity measurements.

7 ACKNOWLEDGEMENTS

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