Soil Erosion Rates from Mixed Soil and Gravel Surfaces in a Wind Tunnel

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SOIL EROSION RATES FROM MIXED SOIL
AND GRAVEL SURFACES IN A WIND TUNNEL

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SUMMARY

Wind erosion tests were performed in a controlled-environment wind tunnel to support the development of natural-material protective barriers for long-term isolation of radioactive waste. Barrier performance criteria currently being developed and assessed for internal and external barrier performance are expected to include a surface layer that is resistant to wind erosion. The purpose of this study was to perform a series of tests to determine the influence of various gravels mixed with McGee Ranch silt-loam soil on rates of wind erosion. The surfaces were configured to represent worst-case conditions as no protective vegetation or surface crusts were provided. Combined with results of previous tests (Ligotke 1988), these tests completed the initial phase of wind erosion studies for protective barriers proposed in a project test plan (Ligotke 1989). Of all tested surfaces, those protected by pea-gravel admixtures and layers were found to be least susceptible to wind erosion.

Mixed soil and gravel surfaces were prepared, weathered to represent natural wind-blown desert areas, and subjected to controlled wind erosion stresses in a wind tunnel. Other surfaces were prepared by placing layers of gravels on top of compacted soil surfaces. Erosive stresses applied to test surfaces were characterized to provide a means of relating wind tunnel results with actual field conditions. Erosion rates, or surface deflation rates, were measured primarily by mass balance techniques.

Measured surface deflation rates varied greatly; at the 20 m/s wind speed, and excluding the soil-only data, the greatest measured deflation rate, $38 \text{ g}/(\text{m}^2\text{-s})$, was about 7300 times greater than the least rate, $0.0052 \text{ g}/(\text{m}^2\text{-s})$. Gravel size influenced the resistance of surfaces to wind erosion. For gravel sizes less than about 1 cm diameter, wind-hardened crusts formed that greatly limited surface deflation under extended periods of exposure at wind speeds representative of actual field conditions. The addition of 0.28- and 0.67-cm gravels as admixtures or layers to McGee Ranch silt-loam soil provided 54 and 32 times less surface deflation, respectively, than did the soil-only case. Thus, the inclusion of fine-particle gravels reduced erosion rates to $2.3 \pm 1.5\%$ of those occurring from unprotected soil-only surfaces. The fine-particle gravels provided a minimum of 4 to 17 times better surface protection than did large-particle gravels (1.6 and 3 cm).

Increasing the thickness of layered gravels placed on the surface of compacted soil decreased deflation rates; however, the magnitude of the added benefit decreased with each successive layer. For the 0.28- and 0.67-cm gravel sizes, as gravel layers were increased from 0 to 1, 2, and 4 times the mass of a single gravel layer, the added benefit provided by each additional layer decreased. The benefit of the added layers was greatest between 0x and 1x (54 and 32 times), intermediate between

1x and 2x (3.5 and 4.2 times), and least between 2x and 4x (1.3 and 1.1 times). Admixture gravel concentration (varied from 10 to 50%) was shown to influence surface deflation rates only before the development of, under the influence of deflation, a gravel armor comparable to the 1x- or 2x-layered gravels. Both well-graded gravels and crushed-rock (angular) gravels provided only secondary differences when compared with single-size river (rounded) gravels with the possible exception of the well-graded gravels containing about 30%, by mass, particles greater than 1 cm.

Based on the results of wind tunnel tests, the best gravel choice for protective barriers exposed to extreme eolian stresses, for either admixture or surface layers, would be a river or crushed gravel containing particles ranging in size between 0.2 and 0.95 cm [material retained between #10 (Alternative sieve no.) and 3/8 in. sieves]. This mixture is often called "pea gravel." It will be important to exclude large quantities of sand (< 2 mm) from the source gravel because sand-sized particles, especially those smaller than 1 mm, would provide a destructive force by being susceptible to transport by saltation, an especially abrasive condition that can greatly increase rates of eolian soil erosion. Use of both an admixture and gravel surface layer are recommended.

The present study brings to conclusion the first phase of wind erosion tests performed in support of protective barrier development. Second-phase tasks are identified in the project test plan (Ligoike 1989). Continued wind tunnel tests are underway or planned to investigate the influence of sand on the candidate and soil-only surfaces both in saltation and incorporated into the surfaces, surface moisture content, natural surface crusts, vegetation (diffuse and deep root structures), burrowing animals, and other factors such as structures of microterrain. Studies are also needed to investigate wind boundary layers and the potential formation of large-scale wind erosion structures such as sand dunes and blowouts.

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1.0 INTRODUCTION

Protective barriers have been identified as integral components of plans to isolate defense waste on the Hanford Site (DOE 1987a). The use of natural materials to construct protective barriers over waste sites is being considered. Design requirements for protective barriers include preventing exposure of buried waste, whether by natural or human-caused disturbances, and restricting penetration or percolation of surface waters through the waste zone. A barrier design proposed for arid climates such as that which occurs at Hanford (DOE 1987b) employs a series of layers, including gravel and riprap, sand, a low-permeability layer, and soil and gravel mixtures.

Adams and Wing (1986) reported that various aspects of protective barrier performance have been evaluated with both mathematical models and field tests, that these evaluations were continuing, and that additional investigations were planned. Resistance of the barrier surface to eolian forces was listed by the authors as one necessary area of study; both deflation caused by wind erosion and the opposite effect, deposition of sand, have the potential for reducing the effectiveness of the barrier to maintain adequate cover and prevent water infiltration at waste sites. In addition, the design of the composition and depth of the surface layer should also consider resistance to eolian forces. To address these concerns, studies were initiated to evaluate the effects of wind erosion on candidate protective barrier surfaces.

A wind tunnel was used to provide controlled erosive stresses and to investigate the erosive effects of wind forces on proposed surface layers for protective barriers. Mixed soil and gravel surfaces were prepared and tested for resistance to wind erosion at the Pacific Northwest Laboratory (PNL)^(a) Aerosol Wind Tunnel Research Facility. These tests were performed to investigate surface deflation caused by suspension of soil from various surface layer configurations and to provide a comparison of the relative resistance of the different surfaces to wind erosion. Tests included replicates using similar surface configurations so that the test-to-test variations in measured quantities could be established and used as a guideline for subsequent tests. The results of these tests allow identification and ranking of admixture characteristics (gravel particle size and distribution, gravel layer depth, admixture concentration, and particle shape) that potentially influence susceptibility of exposed surfaces to wind erosion.

Planning, testing, and analyzing phases of this wind erosion project were coordinated with other tasks supporting the development of protective barriers (Adams and Wing 1986). These tasks

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include climate-change predictions, field studies (admixture test plots, natural analogs, and evapotranspiration), and modeling efforts, including UNSAT (Fayer and Jones 1990) and BIOPORT (McKenzie et al. 1986). Results of this project are important for the development of a suitable design for the barrier surface, but must be considered along with results of the other tasks. For example, because of possible effects of the wind-resistant surface layer on vegetation, plant growth and viability studies should also be performed. And, although certain fractional gravel covers can reduce soil drying, and thus promote plant growth, excessive covers may reduce plant community viability and greatly restrict soil moisture evaporation. Wind-resistant surfaces must still be able to sustain plant growth and allow drying by evaporation. Burrowing animals are also thought to present a major destructive force at the barrier surface, and the impact of plant community and surface layer composition on animal excavation must be considered.

This report provides results of measurements of deflation caused by wind forces over level surfaces. Section 2.0 reviews surface layer characteristics and previous relevant studies on wind erosion, describes effects of erosion, and discusses wind tunnel modeling. Materials and methods of the wind tunnel tests are discussed in Section 3.0. Results and discussion are presented in Section 4.0, and conclusions and recommendations in Section 5.0.

This report does not consider formation of large structures such as blowouts, other surface disturbances, or deflation caused by water erosion. Water erosion specific to the Hanford Site is being studied currently as a separate part of the barrier development project. Future investigations on the absolute rates of erosion from a selected candidate surface, as influenced by soil moisture content, vegetation, surface crusts, and burrowing animals, are planned as are other deflation and deposition studies. Tests of the wind tunnel to represent natural wind erosion conditions should continue, and the effects of test bed length, air turbulence, and terrain microrelief should be considered.

2.0 BACKGROUND

Protective barrier design objectives are being developed and assessed for internal (water percolation rate downward toward the waste site) and external barrier performance (wind and water erosion, other physical deterioration, and presence of a viable plant community). The composition of the surface layer, a review of wind erosion and the influence of wind erosion on the proposed barrier design, and the suitability of wind tunnel tests to provide useful wind erosion data for protective barrier modeling and design are discussed in this section.

2.1 SURFACE LAYER CHARACTERISTICS

The design of a protective barrier for waste-site containment must include a surface that will continue to isolate the waste in the future. A detailed description of the current barrier design proposed for the Hanford Site is provided in Adams and Wing (1986).

Determination of suitable candidate surfaces requires consideration of many variables, including the potential degradation of the surface over a perceived multi-thousand-year life span. The requirement to provide a surface barrier for such a long period of time potentially limits the usefulness of current technology impervious surfaces such as plastics and asphalt, whether on the surface or in the subsurface, because such materials can be expected to fail in much less than the perceived life span of the barrier. If a natural surface layer is used, it must provide a suitable environment to support a viable plant community and retain water from rainfall and snowmelt in the fine soil reservoir for subsequent release by evaporation and transpiration. Mixing gravel with soil has the potential for limiting deflation caused by wind erosion while still providing a surface with the desired capabilities. An alternative approach of placing a thick layer of gravel on the surface, while protecting the soil surface from wind erosion, could impact plant growth and severely limit surface evaporation, while also enhancing water infiltration and drainage into the barrier's interior. However, a thick gravel cover, while temporarily contributing to decreased barrier performance, would probably not remain stable over a long period of time. It is likely that the combined effects of freeze-thaw, shrink-swell, root pressures, and animal burrowing would produce a mixed soil and gravel morphology, regardless of whether the gravel was initially a surface layer or an admix.

2.2 WIND EROSION

The effects of wind erosion and deposition on natural and cultivated surfaces have been the subject of many decades of study. The potential cost of the loss of valuable topsoil has warranted

sustained investigations primarily of the erosion, or deflation, of sand and soil surfaces. The goals of scientific studies have been both to understand the processes of deflation and to devise methods of stabilizing surfaces from the effects of deflation. The primary reasons such studies have been completed have typically included 1) protection and retention of valuable agricultural soils, 2) control and abatement of fugitive dust from arid lands and mine tailings, and 3) quantification of the resuspension of particles, especially of radioactive materials deposited during fallout from atmospheric weapons tests, or from postulated power plant accidents. These studies provide a background for the current work involving the long-term stabilization of natural surfaces by describing mechanisms of wind erosion; however, wind erosion information specific to the protective barrier was required before selection of materials for barrier construction, and to support site-specific modeling efforts.

Wind erosion studies performed over past decades have revealed important wind and surface characteristics that influence wind erosion. Important properties and characteristics of air include wind speed, turbulence, density, and viscosity. Important properties and characteristics of soil surfaces include soil moisture content; surface crusts; a covering layer of vegetation, gravel, or other material; topography; soil structure; and roughness. Aspects of soil structure influencing resistance to wind erosion include composition (clay, silt, sand, and organic matter); particle size distribution (including gravel mixtures); and the presence of nonerodible aggregates or clods. Bagnold (1941) provided early information on processes of wind erosion, especially as saltation and suspension of sand-sized particles. He also correctly determined the importance of measuring wind stresses, developed several techniques for monitoring wind speed, and performed experiments in the field and in a wind tunnel. Other investigators, including Anderson (1986), have continued the investigation of discrete particles of sand and soil, and their work has led to increasingly sophisticated models of material transport by wind.

The importance of surface characteristics and soil structure in determining the susceptibility of a surface to wind erosion have been studied extensively. Chepil (1945a, 1945b, 1950, 1951, 1952, 1956, 1958) is notable among researchers for studying the influence on wind erosion of many soil parameters. A partial list includes soil moisture content, soil particle and clod size distribution, surface crusts, and soil density. Chepil also investigated changes in soil characteristics such as cloddiness, stability, and crusts exhibiting seasonal variations, and developed procedures for estimating (modeling) potential soil erodibility based on soil characteristics. Other investigators have included Chepil and Woodruff (1963); Chepil, Armbrust, and Siddoway (1964); Bisal and Hsieh (1966); Gillette (1978, 1979, and 1980); Logie (1981 and 1982); Fryrear (1985); Skidmore (1986a and 1987); and Tibke (1986). Gillette primarily investigated desert and arid land soils, and Logie

investigated dune sands. Models of wind erosion have been developed or used by Woodruff and Siddoway (1965), Richardson (1982), Bilbro (1985), Arika et al. (1986), Gregory (1986), Presson and Merva (1986), and Skidmore (1986b).

Extensive efforts to reduce the amount of material transported from exposed surfaces have been made, and the great variety of methods resulting from such studies are an indication of the differences separating individual erosion control needs from each other. Methods of wind erosion control typically either shelter the surface by reducing wind stresses or coat the surface to eliminate interaction between the erodible fraction of the surface layer and wind stress, or use a combination of both. Lyles and Allison (1980); Drehmel, Daniel, and Carnes (1982); Armbrust and Lyles (1985); Maki (1985); Heinsohn and Megherhi (1986); Skidmore (1986c); and Ticknor (1987) have investigated methods of reducing soil erosion using natural material and other windbreak structures, and vegetation. Drehmel, Daniel, and Carnes (1982) and Paganyas and Makhstudov (1984) are among investigators of wind erosion control methods using chemical coatings.

Soil particles are transported by three wind erosion processes: 1) surface creep, 2) saltation, and 3) suspension. Surface creep involves the transport of relatively large particles (about 1 mm and greater in diameter) by sliding or rolling in the direction of the wind vector. Under sufficiently high wind forces, gravel particles may be dislodged and slide or roll downwind. At lower wind speeds, gravel particles may influence the local distribution of wind forces by protruding into the air flow boundary layer to a greater extent than the surrounding surface and deflecting wind forces toward its base. These forces may dislodge smaller soil particles, which may eventually dislodge support for the gravel particle and cause it to rotate to a new position. Rotations perpendicular to the wind vector were observed in the current study; gravel oscillated from one side to the other as support was eroded. A lesser tendency for gravel to move into the wind was also noticed. Logie (1982) also observed movement of spheres and gravel into the direction of the wind vector when placed on a flat dry sand surface.

Saltation (sudden vertical suspension of particles) occurs when wind-induced low pressure forces above a particle are sufficient to overcome attractive forces between the particle and the surface and the gravitational force on the particle. Saltation acts primarily on sand-sized particles about 100 μm in size and is characterized by an initial vertical particle trajectory that is followed by transport back to the surface at a shallow angle. The impact of saltating particles on surfaces can provide a driving force for wind erosion. The kinetic energy of a saltating particle is significant because of its large impact velocity and greater-than-average particle mass. On impact, such particles have been shown to enhance suspension of soil particles, and across surfaces many times longer than the

characteristic saltation hop length, a cumulative avalanching effect may occur. Under the influence of very high wind speeds, small-particle gravel may be transported in a manner similar to that of saltating soil particles. Although soil particles may attain an initial height of 1 m, small gravel particles may be expected to lift only a few centimeters off the surface.

Soil particle suspension, the third process of wind erosion, represents the majority of the loss of surface mass. Suspension occurs under the direct influence of wind forces as does saltation; however, suspension is also influenced by both surface creep and saltation. Suspension of particles often occurs in bursts following dislodgement of surface gravel, or following the impact of saltating particles. Particles transported by suspension are typically smaller than 100 μm and are typically transported in suspension downwind from their point of origin rather than continuing to interact with the surface as is the case for both saltation and surface creep modes of transport.

2.3 EFFECTS OF WIND EROSION ON BARRIER SURFACES

The effects of eolian processes on protective barrier performance are grouped into two categories: deflation and deposition. Deflation effects include loss of surface soil, especially during extreme wind events, which results in a gradual lowering of the surface elevation. Such a decrease in the thickness of a barrier would reduce its capability to prevent water percolation into the waste zone by reducing the volume of the fine soil reservoir (the surface layer) and possibly reducing the viability of the plant community. An additional potentially significant form of deflation involves the formation of surface depressions such as blowouts. These structures are formed because of high wind forces directed toward the ground in the wake of nearby large objects. They may form more spontaneously if stabilizing plants are dislodged. In addition to deflation caused by normal weathering processes, deflation may be enhanced by surface disturbances, whether human-caused or as a result of burrowing animals.

Deposition influences in the field may often include displacement of fine-grained surface soils with deposits of windborne sand-sized particles and the formation of sand dunes. The potential for transport and deposition of sand exists on the Hanford Site, and two sets of sand dune fields and several probable blowouts have been identified in a draft report by R.B. Kasper and C.S. Glantz. One blowout, a bowl-shaped depression having edges stabilized by vegetation, was observed to have a stabilized dune crest about 3 to 5 m above its wind-scoured bottom. Should fine-grained surface soil be displaced with deposits of medium or coarse sand, the capacity of the barrier surface layer to act as a water reservoir could be reduced, as the resulting sandy soil would not provide equal water-holding capacity as the originally placed silt-loam. During such periods, depletion of the fine

soil reservoir could be enhanced as soil particles brought to the surface by animals or natural pedogenic processes are eroded at increased rates under the influence of saltation. In addition, the presence of a sand cover or sand dunes could displace desired species of plants, and thus reduce levels of evapotranspiration.

In the presence of a sustained vegetative community, it is possible that deposition in the form of dustfall could contribute to an overall buildup (inflation) of the surface level without greatly altering the particle size distribution in the surface soil. This possibility is thought to be less likely for above-grade barrier surfaces primarily because wind speeds are anticipated to be greater over barrier surfaces than over the surrounding at-grade surfaces; in conjunction with periodic range fires that may temporarily remove protective vegetation, greater wind speeds would tend to remove deposited silt- and clay-sized particles.

Several characteristics of the proposed protective barrier surface layer and wind forces are considered important in defining the worst-case potential for wind erosion, or deflation, of soil from barrier surfaces. Surface layer characteristics include 1) soil type and particle size; 2) gravel size, layer depth, shape, and percentage of the surface layer; 3) soil moisture content and density; 4) presence or absence of an established plant canopy or a plant root structure (especially following a range fire); and 5) presence or absence of surface crusts, including desert pavement, lichen-cryptogamic, raindrop-impact, and chemical crusts. Characteristics of the wind forces driving deflation and other conditions affecting wind erosion include 1) friction velocity, 2) wind speed, 3) yearly precipitation and temperature cycles, 4) terrain microrelief, 5) burrowing animal mounds, and 6) wind turbulence.

2.4 WIND TUNNEL MODELING

Comparison tests of deflation on different surfaces require that similar erosive forces be applied. These conditions are very difficult to achieve in the field where high wind speeds are infrequent, nonuniform in direction, and inconsistent. However, wind forces are controlled in a wind tunnel to allow replication of wind stresses on exposed surfaces from test to test and to provide a basis for comparing various surfaces.

Differences between laboratory and field conditions must be considered when absolute measurements of deflation are attempted in a wind tunnel. Surfaces or surface crusts may be manufactured in a laboratory or obtained in the field and transported to a laboratory. Boundary layer depth is much less in wind tunnel experiments than under actual field conditions. However, this does not affect relative measurements of deflation because the erosive forces at surfaces are related to

surface shear stresses, which are characterized by surface roughness and friction velocity, both of which can be determined from boundary layer profiles. Wind tunnel mean wind speeds do provide greater surface shear stresses than those in the field because of differences in boundary layer characteristics--for comparison, a correction must be applied (see Section 4.2). Multiple-direction weathering of surfaces in the field, as influenced by prevailing winds, is different than the single-direction weathering in wind tunnels. Although not anticipated to be of first-order importance to measurements of rate of deflation, the effect of multiple-direction weathering could be investigated in a wind tunnel by rotating the test surface within the test section.

Another difference between laboratory and field tests includes the unsteady nature of natural winds. Large-scale turbulence, such as gusts or eddies near objects, may be responsible for initiating deflationary processes such as creep, saltation, and particle suspension in the field. For example, a normally stable surface may deflate during exposure to a 15 m/s (33 mph) mean wind speed because of the occurrence of wind gusts that bring large erosive forces to ground level. Wind tunnel experiments with steady, sustained wind speeds equivalent to the gusts (i.e., equal friction velocities) may be used to investigate the effect of the gusts, or the gusts may be reproduced mechanically in the wind tunnel.

An important difference between laboratory and field tests is the length of the surface over which erosive forces act. Saltation has often been determined to have an avalanching effect on wind erosion. Particles are suspended and then fall back to the surface where their impact causes other particles to suspend. Similar increases in deflation occur because of surface creep. Because of the limited length of the exposed surface in wind tunnels, an avalanching effect could be conservative, and measured rates of deflation would be less than those actually occurring in the field. Fortunately, several techniques exist for measuring the effect of avalanching particles. The length of the test bed may be altered to provide a length much greater than the characteristic saltation path length. Also, fully developed saltating particle concentrations can be developed at the upwind end of test beds using sand grains or spherical glass beads. This approach has been used previously by Fairchild and Tillery (1982) and Borrmann and Jaenicke (1987). In these studies, saltation was shown to increase soil particle suspension rates, but the effect on surface stabilization, or the ability of the surface to develop a protective wind hardened crust, was not investigated. The effect of saltation is anticipated to decrease as a surface crust is formed by weathering processes in the field.

3.0 MATERIALS AND METHODS

Mixtures of McGee Ranch silt-loam soil, river gravel, and minute quantities of fluorescent tracer (tracer was only used during the first six tests) were prepared in flat trays and weathered in a wind tunnel at high wind speed to form surfaces representative of natural windblown desert areas. Gravel size, depth of layered gravel on the surface, percentage of mixture, size distribution, and particle shape were varied to study the relative effectiveness of various gravels to stabilize soil surfaces exposed to wind stresses. Air-flow boundary layers were developed upwind of the test trays, and measurements of suspended particle concentrations were made within the flow boundary layers at the trailing edge of exposed surfaces during some tests. Bulk surface mass loss was characterized, corrected for wind speed and changing soil moisture content, and rates of deflation were calculated. Measurements were performed over 2- to 48-hr periods to determine rates of surface deflation and the potential for each test surface to develop a wind-hardened surface crust.

3.1 WIND TUNNEL FACILITY

All wind erosion tests were conducted at the Aerosol Wind Tunnel Research Facility at PNL. This facility, shown in Figure 3.1, is located on the Hanford Site in southeastern Washington. It contains an environmental wind tunnel in which air flow profiles and boundary layers are closely controlled. The facility is described briefly below; additional information on the facility, wind tunnel, and aerosol science capabilities can be found in Ligothke et al. (1986).

Wind speed, relative humidity, temperature, and lighting are controlled within the wind tunnel. The 70 m³ wind tunnel is constructed of stainless steel, for ease of cleanup, except for the transparent polycarbonate walls and ceiling of the primary test section. Three test sections are used for a variety of environmental and engineering projects. The wind tunnel is operated either closed-loop (recirculating), or in single-pass mode for airborne particles by use of a removable bank of high-efficiency particulate air (HEPA) filters in the return loop. This option allows for simplified air conditioning and provides the flexibility to use the wind tunnel for particle resuspension studies that require clean air at the inlet to the test section. The wind tunnel, designed to contain hazardous and toxic materials, may be operated under negative air pressure. Exhaust flows from the system are passed through scrubbers and sets of HEPA filters.

Air movement within the wind tunnel is maintained by a 1-m diameter variable speed fan operated by a 30-v dc motor. Wind speed profiles and boundary layers are uniform and controlled within the 0.61-m-square (0.37 m²) by 6.1-m-long test section used for all particle resuspension

FIGURE 3.1. Orthographic Projection of the PNL Aerosol Wind Tunnel Research Facility

experiments. Maximum attainable velocity 30 cm above test surfaces is 31 m/s (70 mph) for normal operating conditions; however, with modifications, velocities to 50 m/s (120 mph) may be achieved. A reducing section at the inlet to the primary test section and turning vanes in all four bends limit upstream boundary layer depths and provide test section air flows having uniform horizontal and vertical velocity profiles. A 10- to 23-cm-deep false floor is provided below the aluminum plate floor of the test section.

During the wind erosion studies discussed in this report, trays used to contain surfaces for resuspension experiments were placed on top of the aluminum floor or within the false floor, depending on tray height. A mass balance was placed under the test trays during most tests. Roughness elements or actual weathered admixtures coated with a surface fixative were placed upwind of the test surface to provide a realistic boundary layer and to prevent scouring of the upwind edge of test surfaces.

Environmental conditions within the wind tunnel are set and monitored using a computer control and data acquisition system. The system is also connected to aerosol generators and

measuring devices to provide a systematic method for test operation and data acquisition. Temperature is measured by thermocouples, and humidity is measured optically using chilled mirrors; the achievable temperature range is -2 to 50° C (28 to 120° F). Lighting for the test section is provided by 400-W metal halide lamps, and additional ultraviolet (UV) lamps and UV-transparent plexiglass windows are available. Aerosol characterization instrumentation is available to measure concentration, particle size distribution, and composition of a wide range of airborne materials. Facility instrumentation also includes a remote laser single-particle analyzer for nonintrusive measurements of particle concentration, size, and velocity.

3.2 CLIMATE AND EXTREME WIND EVENTS

An understanding of the wind forces at the Hanford Site was required to determine the range of natural wind speeds likely to impact protective barriers. In addition, a comparison of the surface shear forces between the field and the wind tunnel was necessary to determine the range of wind speeds actually used during wind tunnel tests of the relative rates of erosion from bare-surface soil and gravel admixtures. Knowledge of the magnitude and duration of wind events are also important in developing planned predictive models for soil transport and surface deflation, as is understanding the relationship between average wind events and turbulence, specifically peak gust frequencies, speeds, and durations. Wind direction information is also necessary for related studies of sand transport and deposition on barrier surfaces. Other climatological parameters such as seasonal precipitation and temperature cycles (including freeze-thaw cycles) strongly influence wind erosion potential, primarily by affecting soil moisture content (SMC), surface composition and structure, and the development and maintenance of surface crusts. These parameters also must be considered in developing predictive models. In addition to wind forces, precipitation and temperature cycles must be included in a predictive model of surface deflation. Both parameters influence the SMC of surface soil and the duration of time that surface soil remains moist following a precipitation event. Temperature and precipitation data display strong diurnal and seasonal variations and were characterized for the Hanford Site by Stone et al. (1983).

3.2.1 Hanford Wind Forces

More than 40 years of detailed meteorological data have been collected at the Hanford Site. Stone et al. (1983) summarized these data for 1946 to 1980. Hourly average wind speeds from these studies for each month are shown in Figures 3.2 and 3.3 for five elevations: 2, 15, 30, 61, and 122 m (7, 50, 100, 200, and 400 ft). Hourly and seasonal variations in mean wind speed and boundary layer shape also are shown in the figures. Table 3.1 shows the percent frequency of

FIGURE 3.2. Hourly and Monthly Average Wind Speeds for Five Elevations at the Hanford Site--January Through June; PST = pacific standard time (Stone et al. 1983)

FIGURE 3.3. Hourly and Monthly Average Wind Speeds for Five Elevations at the Hanford Site--July Through December; PST = pacific standard time (Stone et al. 1983)

TABLE 3.1. Percent Frequency of Monthly and Annual Wind Speed at 15 m (50 ft) Elevation. Wind speed [m/s] = wind speed [mph] + 2.23. (Stone et al. 1983)

Speed Class mph	Jan	Feb	Mar	Apr	May	Jun
0	5.4	3.2	1.0	0.7	0.7	0.6
1-3	31.9	26.8	18.4	14.8	14.2	11.0
4-7	31.4	31.4	32.7	31.9	32.9	34.2
8-12	19.6	23.9	26.5	27.8	29.0	28.7
13-18	7.3	9.4	13.7	15.9	16.1	17.5
19-24	2.8	3.3	5.5	6.7	6.0	6.7
25-31	1.1	1.5	1.9	2.0	1.1	1.3
32-38	0.3	0.4	0.4	0.2	0.1	0.0
39-46	0.1	0.1	0.0	0.0	0.0	0.0
>46	0.0	0.0	0.0	0.0	0.0	0.0
Total (%)	100.0	100.0	100.0	100.0	100.0	100.0
Jul	Aug	Sep	Oct	Nov	Dec	Annual
0.4	0.8	1.4	3.1	5.5	6.8	2.5
13.2	16.9	20.7	28.5	32.9	32.9	21.8
37.8	38.6	37.4	35.2	32.0	29.9	33.8
27.9	26.3	25.4	21.8	18.9	19.0	24.6
14.3	12.5	10.8	7.9	6.9	7.1	11.6
5.4	4.2	3.6	2.7	2.7	2.9	4.4
0.9	0.7	0.7	0.7	0.9	1.1	1.2
0.0	0.0	0.0	0.1	0.2	0.2	0.2
0.0	0.0	0.0	0.0	0.0	0.1	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	100.0	100.0	100.0	100.0	100.0	100.0

monthly and annual wind speed at an elevation of 15 m. Again, seasonal variations are shown, with summer months generally having less intense wind speeds. Figure 3.4 shows the period of occurrence of peak gust velocities for three elevations: 15, 61, and 122 m (50, 200, and 400 ft). These data were obtained between 1955 through 1980 (Stone et al. 1983). This limited period of record reduces the confidence with which extreme wind gust events may be estimated; however, at an elevation of 15 m, the 100-year peak wind gust may be linearly extrapolated from the figure to be about 38 m/s (85 mph). Continued extrapolation of the data set indicates a 1000-year peak gust of 44 m/s (99 mph) and a 10,000-year peak gust of 51 m/s (114 mph). Estimates of peak wind gusts for greater than 100-year-occurrence intervals are not considered reliable, but are included to provide guidance for determining an appropriate range of wind forces for wind tunnel tests.

FIGURE 3.4. Peak Wind Gust Return Period Probability Diagram, Based on Records 1945 Through 1980 (Stone et al. 1983)

3.2.2 Comparison of Wind Tunnel and Field Measurements

Wind speeds measured in a wind tunnel provide significantly greater surface shear stress than equal wind speeds measured in the field. For example, erosive stress present in the field at a wind speed of 30 m/s (67 mph) might be replicated in a wind tunnel using a wind speed of about 20 m/s (45 mph). This difference between laboratory and field measurements is caused by differing depths and shapes of air-flow boundary layers and because most measurements of mean velocity in the field are made at distances high above the ground surface; 10 and 15 m elevations are often used by meteorological stations. Most wind tunnels provide free-stream wind speed measurements at elevations of less than 1 m, and have boundary layers of even less depth. Typical Hanford Site boundary layers were determined from information presented in Stone et al. (1983) and are presented in Figure 3.5. The figure shows that wind speed at 10 or 15 m elevation can be much greater than the speed closer to the ground.

Erosive forces in the field are modeled in the laboratory by reproducing the shear forces existing at the air-surface interface. Two terms that are useful for relating laboratory and field data are friction velocity and roughness height. Friction velocity, u^* , is a term with units of length

$$u^* = (\tau_s/\rho_o)^{1/2} \quad (3.1)$$

divided by time, hence the name velocity, and is calculated as the square root of the quotient of the surface shear stress (force/area) divided by the air density (mass/volume). Surface shear stress is the average surface shear force divided by the projected area of exposed surface. Because a direct measure of surface shear stress is difficult to obtain, friction velocity is calculated as a function of the shape of the boundary layer immediately over the surface. Roughness height is a measure of the aerodynamic roughness of a particular surface, and thus, its capacity to provide aerodynamic drag on air flowing over it. It is influenced by, but not equal to, the average or maximum height of surface roughness elements such as gravel, tilled ridges, or vegetation. Roughness height is also measured as a function of the air-flow boundary layer. Roughness heights are typically about one-tenth of the apparent average height of surface relief.

The range of friction velocities anticipated in the field must be replicated in the laboratory. Roughness heights and friction velocities typical of many classes of surfaces were summarized by Sehmel (1980, 1984). The wind speed range considered by Sehmel, 1 to 40 m/s, provided an appropriate range for the current study. Level desert was described to have a typical roughness height of 0.03 cm. The friction velocity over such a surface was shown to be 1.81 m/s for a mean wind speed of 40 m/s (89 mph) measured at an elevation of 2 m. Ligotke (1988) performed wind

FIGURE 3.5. Typical Hanford Site Wind Speed Boundary Layers at 0100 and 1200 hr (calculated after Stone et al. 1983)

tunnel measurements over two types of soil and gravel mixtures that had been selected for possible use on protective barriers. The surfaces were weathered by exposure to high wind speeds before measurements were made of roughness height. The roughness height of a 30% admixture of soil and 0.67-cm gravel was shown to be 0.041 ± 0.008 cm, and that of a 30% mixture of 1.6-cm gravel was shown to be 0.10 to 0.37 cm. Because Sehmel's level desert classification was shown to be approximately aerodynamically similar to the 0.67-cm gravel and soil surface, the range of friction velocities anticipated in the field on the Hanford Site were determined by comparison with that surface.

Boundary layers for the Hanford Site (Figure 3.5) indicate that the magnitude of the mean wind speed at an elevation of 2 m is approximately 1.5 ± 0.2 times less than that occurring at 15 m. However, this factor may be conservative because of possible boundary layer distortions caused by gusts, and because of probable scouring at the upwind edges of above-grade protective barriers. Assuming no boundary layer disturbance, the roughly approximated 10,000-year wind speed of 51 m/s (114 mph) at 15 m would correspond to an upper velocity range of 30 to 42 m/s (67 to 95 mph) at an elevation of 2 m. The upper value of this range agrees well with the highest wind speed discussed by Sehmel (1984), and the indicated total range of friction velocities required for wind tunnel tests of the 0.67-cm gravel and soil surface is thus approximately 0 to 2.0 m/s. Figure 3.6 shows additional results of measurements made by Ligothe (1988). Measurements at 10 m/s over a

FIGURE 3.6. Friction Velocities Measured Over a Plastic Spray-Coated 30% 0.67-cm Gravel and Soil Surface with a Roughness Height of 0.41 ± 0.08 mm (Ligotke 1988)

similar bare surface (not sprayed with PVC fixative) resulted in a roughness height of 0.49 mm and a friction velocity of 0.83 m/s (nearly identical to that over the coated surface). A friction velocity of 2.0 m/s was thus developed over the 0.67-cm gravel and soil surface at a wind tunnel free-stream wind speed of 25 m/s (56 mph), and that wind speed was then selected as the maximum for wind tunnel tests.

As a result of this comparison of field and laboratory conditions, it was determined that wind tunnel tests should be performed at wind speeds to about 25 m/s. As surface roughness increases (for example, in the case of 1.6-cm or larger gravel of sufficient concentration or surface cover, or in the presence of vegetation) the test velocity should remain constant; however, the erosive forces during such tests would likely be greater than those during tests with the 0.67-cm gravel surface because of greater aerodynamic drag of the rougher surfaces. An exception to this conclusion would be expected to occur if the fractional cover provided by large-diameter gravels or plants was small, resulting in deflection of scouring wind forces between individual rocks or plants.

3.3 SOIL AND GRAVEL CHARACTERISTICS

Soils from two locations on the Hanford Site have, in the past, been considered for use in constructing the surface layer of protective barriers, the primary location, the McGee Ranch, and a location termed Area 1 (Figure 3.7). Only silt-loam soil from the McGee Ranch site was used in the

present study, as that soil has been characterized and found to have a greater fraction of silt and clay necessary for water retention than did the soil from Area 1. Two 55-gal barrels of surface soil were used during FY 1987 and FY 1988. Four additional barrels were obtained at the same 200 yd³ borrow pit south of the well site at McGee Ranch for FY 1989 tests and again for FY 1990 tests. Analysis of the soil used during FY 1989 wind erosion tests indicated a sand content (particle sizes between 50 and 2000 μm) of 36 to 40%. Last et al. (1987) performed a textural analysis of McGee Ranch soils used in lysimeter studies and reported a particle size distribution consisting of 32 to 44% sand, 42 to 59% silt, and 7 to 16% clay-sized particles. In another study, soil from Area 1 was found by Myers (1985) to contain approximately 30% fines.

Seven types of gravels were prepared, characterized, and used in preparing admixtures for bare-surface wind erosion tests. Six of the prepared gravels were classified visually as river gravels, rather than crushed gravels, because they had predominantly rounded edges; the seventh gravel was purposely prepared from a crushed rock source and had predominantly angular edges. All gravels other than the pea gravel used during the FY 1987 tests were obtained from ACME Concrete

FIGURE 3.7. The McGee Ranch and Area 1 in the Western Region of the Hanford Site in Southeastern Washington State

Company, Richland, Washington. Pea gravel for the FY 1987 tests was supplied by Rockwell Hanford Company. Although of unknown source, it was similar in appearance and particle size distribution to pea gravel obtained subsequently from ACME Concrete Company. Another gravel (3/4 in. concrete mix) of unknown source and used in lysimeter studies was obtained and characterized, but was not used because its constituent rocks were of both smooth river and angular crushed origin. Because particle shape was a test parameter, only rounded river or angular crushed source gravels were used to prepare gravels for the wind erosion tests. Particle size distributions of source gravels were determined according to Method D422-63 (ASTM 1984); the method was modified by using additional sieve sizes to provide finer particle size segregation. Narrowly distributed size fractions were separated from the source gravels by sieving and were used to prepare five gravels used in wind erosion tests. Average particle sizes for these gravels were determined by averaging the sieve sizes passing and retaining material, with calculations weighted for percentage retained in the initial analysis of the source gravels. Weighted fractions of four source gravels were used to prepare the two gravels having widely distributed particle sizes. Average particle sizes for these two gravels were determined by calculation and by sieve analysis.

Gravels with narrow particle size distributions, or single-size gravels, were prepared from one source gravel. Four single-size river gravels were prepared that had average particle diameters of 0.28, 0.67, 1.6, and 3 cm. One single-size crushed-rock gravel was prepared with an average particle diameter of 0.64 cm. The 0.28-cm gravel was prepared from washed 3/8-in. pea gravel by collecting all material passing a U.S. Series Alternate No. 6 sieve (0.333 cm) and retained on a No. 10 sieve (0.200 cm), or a Tyler Series No. 9 (0.198 cm) sieve. The 0.67-cm gravel was also prepared from washed pea gravel by collecting material passing a 3/8-in. sieve (0.95 cm) and retained on a No. 4 sieve (0.475 cm). The 1.6-cm gravel was prepared from a washed 3/4-in. concrete mix source gravel and consisted of material retained between 3/4-in. (1.91 cm) and 1/2-in. (1.27 cm) sieves. The 3-cm gravel was prepared from a washed 1.5-in. river gravel and consisted of material retained between 1.5-in. (3.8 cm) and 1-in. (2.5 cm) sieves. The 0.64-cm single-size crushed-rock gravel was prepared from unwashed 3/8-in. crushed rock by collecting material passing a 3/8-in. (0.95 cm) sieve and retained on a No. 4 (0.475 cm) sieve. In general, the range of particle sizes present in these single-size gravels was ± 20 to $\pm 37\%$ (average = $\pm 28\%$) of the mean particle size (e.g., the 0.28-cm gravel included particles with sieve diameters ranging from 0.20 to 0.33 cm).

Two well-graded gravels were prepared by combining four selected fractions from three washed source river gravels: 3/8-in. pea, 1/2-in. to 1/4-in. roofing mix, and 3/4-in. to 3/8-in. concrete mix. Two fractions of pea gravel were used, previously sieved material that had passed a

No. 4 sieve and standard pea gravel. Based on measured particle size distributions of the source gravels, mixed combinations of the four source gravels were identified to yield gravels with particle sizes ranging from 0.2 to 2 cm (Mix 1) and 0.2 to 1 cm (Mix 2). Mix 1 was prepared from 29% fine pea gravel, 19% pea gravel, 30% roofing mix, and 22% concrete mix. Mix 2 was prepared from 52% fine pea gravel, 42% pea gravel, 6% roofing mix, and 0% concrete mix. Both prepared gravels were analyzed for particle size distribution after mixing and found to have equal to or slightly less than calculated mean particle sizes, and approximately log-normal particle size distributions. Mix 1 was found to have a mean particle size of 0.57 cm and a geometric standard deviation (GSD) of 1.82. Mix 2 was found to have a mean particle size of 0.45 cm and a GSD of 1.46. A sketch of the distributions of all seven types of prepared gravels is shown in Figure 3.8.

In addition to gravel type (rounded river rock or crushed gravel) and particle size, the bulk, packing, and solid rock densities of most of the prepared gravels were measured. The single-size river gravels (0.28, 0.67, 1.6, and 3 cm) had a bulk density of $1.81 \pm 0.01 \text{ g/cm}^3$, a packing density of $64.9 \pm 0.7\%$, and a rock density of $2.79 \pm 0.03 \text{ g/cm}^3$. The well-graded gravel mixture, Mix 2 (0.45 cm), had slightly greater bulk and packing densities of 1.87 g/cm^3 and 67.3%, although the rock density was very similar to the single-size river gravels at 2.78 g/cm^3 . Mix 1 (0.57 cm) and the

FIGURE 3.8. Approximate Particle Size Distributions of Gravels Processed for Use in Wind Tunnel Surface Stability Tests. Single-size gravels shown as solid lines, crushed-rock (angular) gravel shown with short dashed line, and well-graded gravels shown with long dashed lines.

gravel made from angular crushed rock (0.64 cm) were not analyzed. A likely reason for the slight (3.5%) increase in bulk and packing density of Mix 2 compared with the single-size gravels, was increased packing efficiency of particles having dissimilar diameters.

3.4 PREPARATION OF TEST SURFACES

Soil, gravel, water, and tracer combinations were mixed, stored in a manner that prevented drying, and packed in a consistent manner into shallow pans or trays. Several additional trays were prepared to use upwind of the test trays to modify the air-flow boundary layer approaching the actual test surfaces. After preparation, all admixture trays except those used in the gravel layer tests, were weathered by exposure to high wind speed. This was done to provide a bare, uncrusted surface representative of natural unvegetated windblown areas. The surfaces of the boundary layer trays were then coated with a fixative to prevent erosion. Layered gravel surfaces were prepared over compacted soil; they were not weathered pre-test.

3.4.1 Soil, Gravel, and Tracer Mixing Procedures

Gravel, water, and tracer materials were added by mass percentage to preconditioned soil batches. For example, to make a typical 100-kg batch having 30% gravel, 30 kg of gravel was added to 70 kg of soil. Before mixing, soil was passed through a 3/8-in. (0.95 cm) sieve and then through a No. 10 sieve (0.20 cm)--a No. 6 sieve (0.33 cm) was used in FY 1989--to remove sparse organic matter and break up clods. The amount of material removed from the conditioned soil was estimated in FY 1989 to be less than 0.5% of the source soils. Soil was conditioned in this manner to provide a worst-case unprotected soil surface for wind erosion tests. Water was added to the soil during the mixing procedures during the FY 1989 tests to increase the soil moisture content (SMC) to 4%. In FY 1987 and FY 1988, the natural SMC was about 4%, but the soil for the FY 1989 tests was obtained after a dry period and had an SMC of only 1.9%. Tracer material, fluorescent sodium fluorescein (uranine) dye, was added to the mixture (one part dye per 10,000 parts soil) only in FY 1987. This was done to provide a secondary method of quantifying the soil mass eroded from test surfaces.

An initial trial batch of soil and 0.67-cm gravel was mixed using 21 repetitions of the cone-and-quartering method, after removing agglomerated material using rollers. This method provided adequate soil-gravel mixing; however, the tracer tended to agglomerate and was visible as occasional yellow spotting in the mixture. All subsequent mixtures, with and without tracer, were prepared using a concrete mixer. When tracer was added, approximately 1% of the soil was removed, dried in a desiccating oven, and then mixed with tracer powder and returned to the batch in the concrete

mixer. Soil and gravel were mixed for approximately 15 min. Completed mixtures were immediately removed from the mixer and stored in sealed plastic bags. Pre-test SMC was measured at the time the mixtures were used to prepare test surfaces.

For the layered gravel tests (tests 43 through 62, see Section 4.1), gravel similar to that used during the single-size gravel tests was prepared and placed on top of soil-only surfaces that had been packed to an elevation just above the edge of the test trays, using the same methods described for the other test series. The mass of gravel required for each test configuration was then calculated, assuming the layers were placed on the soil in a packing density of 1.8 g/cm^3 . Thus, for 0.28-, 0.67-, 1.6-, and 3-cm gravel, masses of 1.2, 2.8, 6.7, and 12.5 kg, respectively, were calculated to be required to provide a single layer (1x) of gravel on the surface. Trial placement of the gravel on the soil-only surfaces revealed that in shallow layers the gravels did not pack densely. To avoid multiple layering of gravel, mass was removed until a single uniform layer of gravel remained. The actual masses used for a single layer of the 0.28-, 0.67-, 1.6-, and 3-cm gravels were 0.84, 1.8, 4.0, and 7.4 kg, respectively, or roughly two-thirds of the calculated amounts. For double and quadruple layers, nominally two and four times (2x and 4x) times the characteristic dimension of the gravels in depth, these masses were increased by two and four times. Photographic documentation was made of all 20 gravel layer test surfaces.

3.4.2 Test Trays

Test trays consisted of shallow rectangular sheet metal pans that contained and supported test surfaces during wind erosion tests. The trays, shown in Figure 3.9, were 5.1-cm tall, 50.8-cm wide, and 45.7-cm long. A 3.8-cm-tall support ring was used to allow soil and gravel mixtures to be packed to a depth greater than 5.1 cm; the ring was only removed during wind tunnel tests. The surface area of the trays was $2310 \pm 25 \text{ cm}^2$.

Soil mixtures were removed from storage, massed, and packed into the trays to achieve an initial, or target, density of about 1.6 g/cm^3 . The mixtures were compacted by repeatedly applying a compressive pressure of approximately 13 kN/m^2 (using a lead brick on its long side), a technique sufficient to pack 30% admixtures of 0.67-cm gravel in McGee Ranch silt loam soil to the target density. The compaction technique was similar for all trays; soil-only trays tended to pack to densities of 1.3 to 1.4 g/cm^3 , and admixtures of the larger gravel particle diameters tended to pack to bulk densities of 1.7 to 1.8 g/cm^3 . Using the support ring, soil and gravel admixtures were packed to a height equal to or greater than one gravel particle diameter above the top of the tray. Edges were left square for the early tests, but were trimmed at an angle of 45° before later tests to reduce the influence avalanching side walls on bulk tray mass. The extra packing height was required to allow

FIGURE 3.9. Schematic View of Test Tray and Support Ring

pre-test conditioning (simulated weathering) of the surface and to eliminate any potential effects of exposed tray edges. The density of prepared trays was determined by comparing the mass and volume of the compressed mixture. Uncertainties in mass were insignificant, and potential errors in volume were limited to uncertainty in average height of the mixture, which was estimated by observation to be ± 0.3 cm. The magnitude of the uncertainty in density should thus have been limited to $\pm 5.4\%$, or approximately ± 0.09 g/cm³.

Trays were stored after preparation, overnight during some tests, and post-test using sealed plastic covers to limit loss of soil moisture. Measurements indicated no significant loss of water occurred during storage periods. The tray ring was inserted, and a plastic sheet was taped securely over the top of the ring, approximately 3 cm above the surface. The seam between the ring and the tray was also taped. Measurements of tray mass indicated a consistent loss of mass, which after 21 days totaled about 15 g, or 0.1% of the total mass. Assuming a SMC of 4.0%, and that all the measured mass loss was because of water loss, such a mass loss would correspond to 2% of the SMC, or a decrease from 4.0 to 3.9%. Layered gravel test surfaces were tested immediately after preparation.

3.5 TEST PROCEDURES

Test procedures varied slightly from year to year as experience gained testing admixture surfaces led to increasingly more effective and sophisticated measurement techniques. For example, fluorescent tracer was added to the admixtures in FY 1987, but not in subsequent years because the dye was shown not to increase measurement sensitivity. A mass balance was placed into the wind tunnel under the test trays during FY 1988 and FY 1989, thus eliminating the need to move heavy test trays repeatedly in and out of the wind tunnel for measurement and facilitating the collection of greater numbers of samples. Tests during FY 1988 and FY 1989 included fewer aerosol samples, as bulk surface mass measurements had been shown to provide sufficient data (Ligotke 1988). Similarities in test procedures over the 3 years of testing were also important. In all years, test results were comparable because test surfaces were exposed to wind forces modified by the use of air-flow boundary layer trays and characterized to provide quantification of surface shear stresses. Also, pre-test and post-test SMC of the admixtures was obtained in all years for both surface and bulk samples.

3.5.1 Surface Weathering

Newly prepared test surfaces did not resemble natural windblown surfaces until they were conditioned, or weathered, by exposure to high wind speeds in the wind tunnel. After initiating each test, the conditioned surfaces were subjected to wind stresses in the wind tunnel for increasingly long durations, a process that was called aging to distinguish it from the similar process of pre-test weathering.

Initially, most surfaces resembled the soil-only test cases. Only the tops of a small number of gravel particles were visible at the surface. After completion of the weathering process, admixture surfaces resembled natural windblown surfaces--with gravel exposed and the admixture surface shaped by the influence of wind forces and the characteristics of the soil and gravel. For most surfaces, the rate of soil particle suspension caused by weathering at a wind speed of 20 m/s was initially very large, then decreased dramatically and approached a steady state. Weathering was continued until the original surface had been deflated by about the characteristic dimension of the gravel particles. All admixture test surfaces were weathered before wind erosion tests; layered gravel surfaces were tested without pre-test weathering.

Trays were placed in the wind tunnel test section behind boundary layer surfaces and marked with the direction of the wind vector. During weathering tests, the wind tunnel was typically operated at wind speeds of 5, 10, 15, and 20, 22, or 25 m/s (11, 22, 33.5, and 45, 49, or 56 mph)

for 10 to 65 min to deflate the surface by the characteristic dimension of the gravel in the admixture. The actual weathering history was judged less important than the depth of deflation caused. Soil-only surfaces were deflated about 0.5 to 1.0 cm. Surfaces of admixtures containing the 0.67-cm and smaller gravel particles consistently weathered uniformly; however, especially for the 1.6-cm gravel, admixtures of the two larger gravel particle sizes tended to form an irregular surface with deep channels (with depths sometimes greater than the diameter of the gravel particles). The channels were oriented roughly parallel to the wind vector. Observations revealed that small particles consisting of surface dust and organic matter were suspended at the lower weathering velocity; however, nearly all deflation occurred at the highest wind speeds. At 10 m/s, gravel began to become visible after approximately 5 min as the surface soil was removed. Noticeable soil particle suspension occurred near the edges of gravel particles--in areas of probable maximum wind shear--and gravel particles shifted occasionally as supporting soil was displaced. At 15 to 25 m/s, movement of exposed gravel became frequent, and some gravel saltation was evident for gravel sizes less than 1.6 cm. Soil particle suspension and gravel saltation occurred in bursts, as anticipated; one event would destabilize a region and result in a short burst of suspended material. Effects of gravel creep and saltation were similar. As gravel particles bounced along the surface, they dislodged other particles, causing a temporary avalanching increase in saltation activity.

Weathering periods for the admixtures containing the 1.6- and 3-cm gravels were longer than for the smaller particle gravels. This was necessary to deflate the surfaces to the greater depth representative of the gravel particle diameters. The result of the weathering process for the trays containing large-diameter gravels was similar to that for the small-diameter gravels with the following two noticeable differences: 1) initial erosion rates at the greatest wind speeds were less than those observed for the small-diameter gravels, and 2) pronounced surface channeling occurred. The initial lesser rate of erosion was attributed to the larger size of the gravel for several reasons: 1) the lower surfaces of the large gravel particles were not exposed until a greater depth of soil had been removed, possibly reducing deflected wind shear forces; 2) the larger gravel particles did not vibrate or shift position as rapidly as the smaller gravel particles, even when mostly exposed above the surface; and 3) rapid downwind dislocation of the large gravel particles was extremely rare, and thus resulted in a reduced influence on soil particle suspension when compared with the movement that occurred on the surfaces of admixtures of the small-diameter gravels. Although initially slow, erosion rates from surfaces protected by large-particle gravels seemed to increase as the surface developed, primarily because the greater height of the gravel disturbed the air-flow boundary layer at higher elevations (regions of greater velocities), thus deflecting greater shearing forces to the air/soil interface. Surface channeling was also thought to have been caused by the large particle size. Natural, uneven distribution of gravel protruding into the boundary layer would likely cause

localization of scouring shear forces, and the locations of resulting increased particle suspension would tend to propagate downwind. Channels were characterized by a direction roughly parallel to the wind vector and maximum depths of 2 to 3 cm.

3.5.2 Boundary Layer Surface

Test surfaces were provided with uniform and quantifiable wind shear stresses. Air-flow boundary layers approaching test surfaces were modified by exposure to the frictional drag of a surrogate, or boundary layer, surface 51-cm wide and 46- or 69-cm long, positioned upwind of test surfaces during all tests. The surrogate surface provided a developed air-flow boundary layer within about 7 cm of the test surfaces. The shape of the boundary layer, or the velocity of air close to a surface relative to the free stream velocity, was influenced by a number of conditions, including the morphology of the surface. The flat aluminum plate surface of the wind tunnel test section floor provided little resistance (frictional drag) to air flow, and velocities close to its surface were relatively fast when compared with the rougher test surfaces. The rough boundary layer surfaces provided a greater degree of resistance to flow, and thus the relative velocity of air close to the test surfaces was slowed. Scouring velocities approaching test surfaces along the floor of the wind tunnel test section were thus decreased, and boundary layers were formed prior to contact of wind with the test surface. Boundary layer characteristics were measured for the various tested surface configurations and wind speed conditions to provide information on aerodynamic surface roughness and surface shear stress.

In addition to forming a steady boundary layer upwind of the test trays, turbulent eddies over the test surfaces, other than those caused by surface morphology, were minimized by beginning tests with the lip of the tray edge below the surface and using flat flow guides at both sides of the test surfaces. Turbulence associated with tray edges was avoided because it was thought that eddies developing along or leeward of exposed edges would artificially increase wind erosion rates in a manner difficult to characterize or replicate.

Three types of boundary layer trays were constructed, weathered, and spray-coated with a thin layer of water-soluble polyvinyl alcohol (PVA). The boundary layer trays were made representative of soil-only, 0.67-cm, and 3-cm gravel admixtures. Gravel concentrations were 30%, by mass. The PVA surface seal allowed use of the boundary layer trays to create an air-flow boundary layer, and eliminated deflation as a result of erosion--thus eliminating possible interference with deflation measurements over the test admixture surfaces. Two or three boundary layer trays were placed in series upwind of the location occupied by the individual test trays during wind erosion tests. Either number of boundary layer trays appeared to sufficiently condition the air-flow boundary layer. Measurements of air-flow boundary layers at the downwind edge of the boundary

layer trays were different from those above the aluminum plate floor, but similar to those measured above the downwind edge of the test trays (see Section 4.2). These results indicated that the boundary layer trays were required, and that the method used was sufficient.

Most tests were performed using the 0.67-cm gravel boundary layer trays after boundary layer measurements indicated no great differences in air-flow boundary layers over surfaces containing gravel sizes less than 1.6 cm (see Section 4.2). Tests of the 0.28-, 0.45-, 0.57-, 0.64-, 0.67-, and 1.6-cm gravel admixtures, and tests of layered gravels, were performed using the 0.67-cm gravel boundary layer trays. Tests of soil-only surfaces were performed in FY 1988 using the soil-only boundary layer trays, and in FY 1989 using the 0.67-cm gravel boundary layer trays. All tests of 3-cm gravel admixtures were performed using the 3-cm gravel boundary layer trays.

3.5.3 Configuration of Test Surface

Test trays were placed individually into the wind tunnel test section immediately behind fixed (nonerodible) boundary layer surfaces as shown in Figure 3.10. The test section was 10 cm greater in width than the trays, and trays were centered with smooth aluminum surfaces installed at both sides at the level of the top of the trays. Trays were constructed smaller than the width of the test section to eliminate exposure of the test surfaces to the nonuniform wind speeds existing at the outer ~7 cm of the wind tunnel test section. This condition was caused by boundary layers next to the walls of the test section. Wind speed was uniform across the width of the trays.

FIGURE 3.10. Cross-Sectional View of Wind Tunnel Test Section Showing Test and Boundary Layer (Fixed) Surfaces, Air-Flow Direction and Boundary Layers, and Aerosol Sampling Probes

3.5.4 Description of Test Sequences

The durations of tests varied from about 1 hr to 3 days. Most standard tests were performed over periods of 1 to 3 days, but tests of gravel layers over soil surfaces were performed in 1 to 2 hr. Tests were occasionally halted overnight during FY 1987, but were continuous during FY 1988 and FY 1989. The test surfaces were covered with plastic during the halted periods to prevent loss of SMC--it is possible that this provided time for the remaining soil moisture to redistribute and possibly to rewet the surface to some extent. The influence of this process on deflation measurements made during FY 1987 was anticipated to be small, but was not quantified.

Each test consisted of a series of measurements, usually performed as wind speed was increased. Although measurements were also performed at other wind speeds, surfaces exposed to wind speeds of 10, 20, and occasionally 25 m/s were aged by exposure to a steady wind speed for about 2 to 24 hr, before increasing wind speed to the next incremental level. Measurements at 10 m/s extended over an aging period of as long as 24 hr, at 20 m/s to 10 hr, and at 25 m/s to 2 hr. Layered gravel and selected other tests were performed over shorter durations. Photographic records, including photographs and video were used periodically throughout each test to document changes to the surface morphology. Surface (0 to 1 cm) and bulk (0 to 5 cm) samples were obtained post-test and analyzed for SMC.

3.6 MEASUREMENTS

Measurements were made during each test to characterize test conditions such as mean wind speed, temperature, and relative humidity. Additional measurements of vertical flow boundary layers were made during selected tests. Surface compositions were identified and morphologies characterized using visual observation and photographic techniques. Deflation occurring during each test was monitored using either or both of two methods--measurement of the bulk mass of the test tray and measurement of the aerosol suspended above the trailing edge of test surfaces. In selected tests, the vertical profile of the suspended particulate soil mass was also measured to provide data for a comparison of aerosol and mass measurement procedures. The SMC of the surface layer and bulk admixtures were also measured during most tests.

3.6.1 Mean Wind Speed

The mean wind speed was defined as the average velocity of air in the undisturbed region above the test surface boundary layer. A pitot-static tube was oriented within 5° of the direction of air flow and at an elevation 20 to 30 cm above the test surface. Mean wind speed was measured at

the beginning and end of individual portions of each test and periodically throughout most tests. One-half of the dynamic versus static pressure difference at the pitot-static probe was measured using a Dwyer Model 1430 micromanometer with 0.0001 in-H₂O readability. Beginning in FY 1988, a MKS Baratron differential pressure transducer No. 398, connected to controller Model 270B and the wind tunnel computer, was used to provide periodic data on mean wind speed. For wind speed data obtained using the micromanometer, and for calibrations of the transducer, atmospheric pressure for the 300 Area was obtained from the Hanford Meteorological Station, and temperature within the wind tunnel was obtained using a General Eastern Model 1500 hygrometer. In addition to the pitot-static probe measurements, a hot film sensor connected to a TSI Model 1054A anemometer was used in FY 1987 to monitor wind speed at centerline in the approach to the wind tunnel test section.

The horizontal wind speed profile over the test surface was measured from one side of the wind tunnel test section to the other above the boundary layer for wind speeds of 5 to 25 m/s to demonstrate the uniformity of wind forces present across the width of test trays. Boundary layer trays and a test tray were present during the measurements. A pitot-static probe was placed in traverse at several locations, and mean velocity measurements were obtained.

3.6.2 Air-Flow Boundary Layer

The vertical air-flow boundary layer was measured during selected tests, over a range of 5 to 25 m/s, but typically at wind speeds of 10 and 20 m/s. Boundary layers were measured over the flat plate aluminum surface of the wind tunnel test section, the trailing edge of boundary layer trays, and the trailing edge of actual test trays during tests (after weathering). Boundary layer measurements were obtained using a pitot-static tube on a vertical traverse. Data were plotted to provide a comparison between the different surfaces tested (aluminum plate, boundary layer, and test surfaces), including differences between boundary layer surfaces of soil-only, 0.67-cm, and 3-cm gravel admixtures, and to provide information allowing calculation of aerodynamic roughness characteristics of the surfaces and the magnitude of applied surface shear stresses.

3.6.3 Threshold Velocity of Soil Particle Suspension

Wind speed was gradually increased at the beginning of most tests so that the speed at which soil particle movement first occurred, the static threshold velocity, could be determined. A remote single-particle analyzer was used to augment these otherwise visual observations by focusing the beam of the HeNe laser within the lower air-flow boundary layer over the trailing edge of the test surface during selected tests. During FY 1987 tests, the analyzer was instead focused 30 cm downwind and 10 cm above the surface (downwind of the isokinetic aerosol sampling probe and

support). Particles that were suspended and diffused in the turbulence behind the isokinetic sampler were detected by the particle analyzer. Isokinetic aerosol samples obtained at 5 and 10 m/s also supported these measurements.

3.6.4 Fluorescent Tracer Material

Use of aerosol probes to measure soil particle resuspension was limited to cases when more than about 0.05 mg could be collected on the filter substrate. Lack of adequate sample mass was anticipated during tests at low wind speed or when a wind-hardened surface crust reduced particle suspension rates. A fluorescent tracer material was mixed with the soil and gravel in FY 1987 to provide an additional method of measurement. Originally, the goal of using tracer was to provide analytical capability for samples containing more than 0.005 mg of soil particle mass, or an improvement of 10 times over gravimetric analysis. A mixture of 1 part sodium fluorescein (uranine) per 10,000 parts soil was determined to provide a suitable level of tracer compared with natural soil fluorescence at the appropriate levels when samples were extracted in water. (The aqueous analysis was more sensitive than using a methanol extraction procedure.) Uranine tracer was added to all FY 1987 soil-gravel batches prepared for resuspension tests.

3.6.5 Isokinetic Aerosol Measurement

Samples of soil particles suspended within the boundary layer at the trailing edge of test surfaces were obtained extensively during FY 1987 and to a lesser degree in subsequent years. These measurements were performed to provide a secondary check of relative rates of deflation over the tested surfaces--the primary measure being bulk tray mass (see the following section). Advantages of the aerosol method included independence from SMC changes that occurred at the surface, and disadvantages included collection of only a limited fraction of total suspended dust sampled. Because only a fraction of the total boundary layer and tray width could be sampled using aerosol probes, and because of the intermittent nature of specific erosion events, the adequacy of this measurement was not known before actual tests and data analysis were completed. Results were compared with bulk tray mass measurements. Use of a sampler equal in area to the air-flow boundary layer was considered but not implemented because of the excessive sample flow rate such a device would have required (~ 1700 cfm at $\Delta P = -6$ in. Hg).

Suspended soil particles were collected on 47-mm glass fiber filters (Gelman Type A/E) and analyzed using gravitational and fluoroscopic methods. All sampling nozzles were sharp edged and were 1.27 cm in diameter and 10-cm long. A manifold was used to operate a series of nozzles during selected test periods. The manifold was connected to a vertical support, and nozzles were

positioned horizontally at one adjustable measured distance above the average test surface during FY 1987. One, two, or three samplers were operated within the surface boundary layer during tests; three samplers were typically operated during tests at 10 m/s and two during tests at 20 m/s. Available high-volume air sampling capabilities limited the number of isokinetic samplers used during the high-velocity tests. In FY 1988 and FY 1989, a larger blower was available, and four aerosol samples were typically obtained during each selected measurement. In addition, an improved manifold was mounted so that each of the four nozzles could be used at the same or different elevations within the air-flow boundary layer. One nozzle was operated periodically at an elevation greater than the height of the boundary layer to provide information on background aerosol concentration in the wind tunnel.

Samples were obtained isokinetically; the velocity of the sample in the nozzle was approximately equal to that in the surrounding air flow. The sharp edges of the sampling nozzles provided little resistance to flow, and nozzle geometry was chosen to limit turbulence within the nozzle. Because most samples were obtained within the boundary layer, the sample flow rate was reduced to less than that required for sampling in the free stream flow. For example, when sampling at an elevation 1.9 cm above the average surface, the sample flow rate was controlled at a rate about 0.74 times that which would have been used had the nozzle been located above the boundary layer. Samples were primarily obtained at an elevation corresponding to a velocity of 0.74 times the free stream velocity; however, samples were also obtained at elevations corresponding to velocities of 0.55, 0.87, and 0.97 times the free stream velocity to provide information on vertical particle concentration profiles.

Because of the inertia of suspended soil particles and the turbulent state of the boundary layer, particles drawn into the sampling nozzles did not always penetrate to the collection filter. This was taken into account in all data analysis procedures, using the results of a series of calibration tests at 5, 10, and 20 m/s. The total amount of deposited mass collected in the walls of a nozzle during selected tests was determined by rinsing the material from the nozzle with a known volume of distilled water and analyzing the resultant solution fluoroscopically. The sampling effectiveness of the probes was then calculated as the amount of soil deposited to the filter substrate divided by the sum of the same mass and the particulate mass collected on the walls of the nozzle.

Isokinetic sample flow rates were measured by passing the sample flow through a flowmeter. A vacuum gauge was also mounted to the discharge of the flowmeter and used to correct flowmeter reading for the reduced density of the sample flow. Calibrations were performed for both devices,

and an analysis of potential errors was completed. During FY 1988 and FY 1989, sample flow rates were monitored using a mass flowmeter that was insensitive to sample pressure.

3.6.6 Surface Mass Loss

The change in mass of admixture surface trays was measured. Change in mass typically represented loss of soil and evaporation of soil moisture. Occasionally, gravel would be moved from the surface by the wind. Use of HEPA filters in the return section of the wind tunnel reduced background aerosol and the potential impact of depositing dust on surface mass.

A Sartorius Model 3807 high-capacity (60 kg) mass balance was used to measure tray mass. The device was mounted in the wind tunnel test section during FY 1988 and FY 1989, and tray mass was obtained directly after turning off the wind tunnel fan and freeing the tray edges from side and front supports. In FY 1987, test trays were removed periodically and weighed. The device provided an accuracy and repeatability of better than ± 1 g, an increment found to be suitable for wind erosion tests. Repeatability was demonstrated by a series of measurements on a single test tray, and accuracy was confirmed periodically by the Hanford Engineering Development Laboratory's (HEDL) Standards Laboratory. Measurement of surface mass proved to be a more effective method of monitoring deflation than aerosol samples, and was used increasingly throughout the project. The mass balance was also used to monitor long-term tray mass loss from presumed evaporation of soil moisture.

3.6.7 Soil Moisture Content

Soil moisture content (SMC) was recognized as a potentially significant factor influencing wind erosion measurements in the wind tunnel, not only because it influenced surface cohesiveness, but also because changes in soil moisture influenced measurements of the overall, or bulk, surface mass. The depth of admixtures in test trays was typically 5 to 6 cm, and each surface initially contained a uniform SMC. At the start of the project, we did not know the influence of surface evaporation, wind speed, duration of drying period, and average SMC on either 1) the distribution of soil moisture within the test trays, or 2) the rate at which moisture from lower regions of the admixtures could potentially re-moisten the surface layer via capillary forces and temperature-dependent vapor-phase water migration. In the absence of predictable soil moisture behavior, SMC was monitored during all wind erosion tests, and special tests were performed of the loss of moisture during pre-test storage, surface layer drying, and vertical profile of soil moisture within the 5-cm-deep trays.

The SMC of each tested surface was measured at least twice, at the time admixtures were prepared and after each test series was completed. Samples were analyzed gravimetrically before and after drying in an oven at 105 to 110° C for about 24 hr, using sampling and analysis procedures similar to those described in ASTM Method D2216-80 (ASTM 1980). The method was modified slightly to allow determination of actual SMC by removing gravel from each sample. This allowed determination of not only the SMC of the admixture, but also the SMC of the soil fraction. The SMC measurements made at the time of admixture preparation were considered identical to pre-test SMC after measurements of surface mass loss while sealed (in the interval between preparation and weathering, and weathering and testing) revealed that very little evaporation occurred during surface storage (see Section 4.3). Two types of post-test samples were obtained and analyzed, surface and bulk samples. Surface samples were obtained by sampling the top 1 cm of soil over an area of approximately 100 cm². Uncertainty of sample depth was estimated to be ± 0.5 cm. Bulk samples were obtained by coring the entire depth of the mixture, approximately 5 cm, within a circular area of approximately 20 cm². Two surface and two bulk SMC samples were obtained after each test.

Three other measurements of soil moisture were performed: 1) a sealed surface tray was massed periodically for 21 days to provide data on the suitability of the plastic and tape seal; 2) the influence of wind on surface drying was monitored for several days by sampling the surface layer at intervals and analyzing the SMC; and 3) a non-destructive SMC monitor was developed and used in FY 1988 to monitor average SMC and the vertical profile of SMC in the tested admixtures. The latter measurements were performed using miniature conductivity probes positioned at two locations within the admixture. The probes consisted of five electrodes spaced 1 cm apart on a rigid mount and were oriented vertically in the admixtures. Data were obtained by applying a potential of about 12 v dc across two electrodes at a time. Data were obtained both across the 15 cm distance between probes and the 1 cm distances between electrodes on the same probe. Power for the same duration during each measurement as conductivity typically decreased slowly with increased duration of applied potential. Analysis of data was performed using a calibration obtained by comparing electrical conductivity to destructive grab samples analyzed using ASTM Method D2216-80 (ASTM 1980). A series of measurements were also made to determine changes in the vertical profile of water moisture for average SMCs of 2 to 8%. Use of the conductivity method was limited by gravel size and concentration.

3.6.8 Instrument Calibrations

Instruments calibrated in the laboratory included the wind tunnel fan controller, a hot film anemometer, two flowmeters, and a vacuum gauge. Instruments calibrated by the HEDL Standards

Laboratory included three mass balances and two flow rate meters. Other devices were calibrated by the manufacturer and supplied with calibration certificates. These included one flowmeter, the micromanometer's micrometer, and temperature and humidity probes. No absolute calibration of the fluorometer was required as all fluorometric data were based on relative comparison of a number of measurements.

Mean wind speed calibrations were performed in the laboratory. The standard for all wind speed measurements and calibrations was a Dwyer Model 1430 micromanometer having an accuracy of ± 0.00013 in-H₂O for $1/2(\Delta P)$, and readable to 0.0001 in-H₂O. Potential errors associated with measurement of mean wind speed, because of limitations of the micrometer, were 0.2% or less. Magnitudes of real velocity fluctuations measured in the free stream flow ranged from 0.2 to 0.6% of the mean velocity for velocities between 5 and 25 m/s.

The flowmeter and vacuum gauge used to measure aerosol probe sample flow rates in FY 1987 were replaced in FY 1988 by a Sierra Model 731 mass flowmeter. The flowmeter used in FY 1987 was a Dwyer No. RMC-106 and was calibrated by comparison with a Dresser No. 1.5M125 roots meter and a Singer DTM-115 dry test meter. Both standards were calibrated by the HEDL Standards Laboratory. The maximum deviation of data from the flowmeter calibration was 5.3% at a flow rate of 35 liters per minute (lpm); the average deviation over a 30- to 400-lpm range was 2.0%. Sample air flow in the discharge of the flowmeter was at less than atmospheric pressure. Because of this, the actual flow rate was a function of both the flowmeter reading and the discharge vacuum. A standard 0- to 30-in.-Hg vacuum gauge was used and was calibrated by comparing it with a mercury manometer. For flowmeter discharge vacuums ranging from 0- to 20-in. Hg, potential errors associated with the accuracy and readability of the vacuum gauge corresponded to flow rate errors ranging from 0.05 to 0.7% (with an average of 0.29%). Errors rapidly increased as the flowmeter vacuum approached absolute (30 in.-Hg); however, flowmeter settings were controlled, and no samples were obtained with the vacuum greater than 20 in.-Hg. The sum of maximum possible flow rate errors was therefore $\pm 6.0\%$, and average anticipated errors were $\pm 2.3\%$.

The Sierra Model 731 mass flowmeter used in FY 1988 and FY 1989 was supplied with a calibration certificate by the manufacturer. However, a calibration check was performed before use and a corrected flowmeter calibration prepared. The device used to verify the calibration of the mass flowmeter was a Dresser Co. Model 1.5M ROOTS meter calibrated by the HEDL Standards Laboratory.

3.7 DATA ANALYSIS PROCEDURES

Data were analyzed sequentially to identify surface characteristics, test conditions, applied erosive forces, and surface deflation rates. Data sheets and analysis calculation sheets were reviewed, photocopied, and stored in two separate locations for possible future reference.

Test conditions included temperature, relative humidity, and wind speed. Mean wind speeds provided the basis for comparison between tests. Vertical boundary layers were analyzed to provide information on aerodynamic surface characteristics and magnitudes of applied erosive shear stresses. Horizontal wind speed profiles were also determined to provide additional information on the uniformity of applied erosive stresses.

Surface characteristics, including SMC, bulk density, gravel type, gravel particle size and size distribution, percentage gravel, and depth of layered gravel were recorded. These records, other than SMC, were used to correlate data for the various categories of completed bare-surface tests. The SMC was analyzed to provide estimates of the percentage of total surface mass loss that was a result of moisture evaporation rather than actual soil particle loss. The initial (~3.5 to 6%) and final (~2 to 3.5%) SMCs of the bare-surface test surfaces were typical of medium to low field levels. Although tests were of similar SMCs, an attempt was made to correlate measured surface deflation rates to SMC. Future tests are planned to address this subject over a wider range of SMC, as SMC was not test a parameter during the present study.

Aerosol sample probe data were analyzed to determine the influence of non-isokinetic sampling and nozzle wall losses. Corrected particulate mass concentrations were used to determine vertical mass concentration profiles, which were then used to determine particulate mass flux from the surface. Results of aerosol sampling probes were also later compared with results of bulk surface mass loss using a gravimetric procedure. Bulk mass losses from the test surfaces were corrected for concurrent losses of soil moisture, based on pre-test, post-test, and vertical profile SMC measurements, and for slight deviations in wind speed from target values. These values were then compared with the exposed area of the test surface to determine surface deflation rates. These rates for each surface were then compared to aging time (at each wind speed) during the experiments to determine the influence on deflation and the stability of wind-hardened surface crusts. Finally, deflation rates of the various tested surfaces were compared with replicate tests (within the same year and between years), and with each other. From this data set, the surfaces tested were ranked for potential resistance to wind erosion.

4.0 RESULTS AND DISCUSSION

Analysis of data collected during wind tunnel tests was completed sequentially as the results of each measurement contributed to the interpretation of other measurements and (finally) to the correct interpretation and qualification of relative surface deflation rates measured in the wind tunnel. Results are presented in order of analysis and begin with a list of tests, surface configurations, and test conditions. Test results are from tests performed in FY 1987 - FY 1989. Wind forces applied to the test surfaces were then characterized and parameterized. Soil moisture content measurements were tabulated. Next, fluorescent tracer and aerosol sampling data were analyzed. Surface mass loss data were tabulated and adjusted for concurrent mass loss as a result of soil moisture evaporation. A comparison of aerosol and surface mass measurement techniques was performed. Finally, relative surface deflation rates as influenced by surface composition and duration and intensity of applied wind stresses were determined.

4.1 TESTS AND SURFACE CONFIGURATIONS

Four series of bare-surface tests were identified in the test plan that guided the present study (Ligotke 1989). These included soil-only, single-size gravel, well-graded gravel, and crushed-gravel. A fifth test series, layered gravel, was also performed, and three tests were performed to provide information on initial rate of deflation at wind speeds of 20 and 25 m/s. Standard tests provided these data only after a wind-hardened crust was formed by exposure to 10 and 15 m/s wind speeds. Bare-surface tests were performed primarily to measure relative rates of surface deflation so that a comparison of the various tested admixtures could be performed. Soil-only tests were performed to provide a baseline comparison for the soil and gravel admixtures. Single-size gravel admixtures were tested to determine the influence of gravel size and concentration on surface stability. Narrow size distributions of washed river gravels were prepared by sieving, as described in detail in Sections 3.3 and 3.4. Well-graded gravels were tested to determine the influence of gravel particle size distribution on resistance to wind erosion. Well-graded gravels were made by mixing quantities of four separate source gravels. Angular-particle gravels were also tested to determine potential differences in surface protection provided by river (smooth) and crushed (angular) particle shapes. Layered gravels having depths of 1, 2, and 4 times (1x, 2x, and 4x) the characteristic particle diameter were tested after it was observed that shallow gravel layers (estimated to be about 0.5 to 1.5 gravel diameters deep) tended to form naturally on surfaces after extended periods of deflation during wind tunnel tests. Layered gravel tests were performed using gravels identical to those used during the single-size gravel tests.

The completed matrix of bare-surface wind erosion tests is shown in Table 4.1. All tests identified in the test plan (Ligotke 1989) were performed, with the exception of the 10 and 50% admixture cases for well-graded Mix 2. Tests not identified in the test plan, but required for comparison of bare-surface test cases were three additional crushed-rock tests (performed to provide information on the initial rate of deflation at wind speeds of 20 and 25 m/s), and the 20 layered gravel tests. Data were analyzed from five soil-only tests, instead of three as specified in the test plan, because data from replicate tests performed as part of a subsequent series of wind erosion tests were available.

The test matrix shown in Table 4.1 was designed to allow statistical testing, based on a fixed-effects, one-way analysis of variance, of the effect of increasing admixture gravel particle size at the 30% mixture. Both linear and simple non-linear models can be developed if a functional relationship caused by gravel size is evident. In addition, the one-way analysis of variance could include the soil-

TABLE 4.1. Bare-Surface Test Matrix (No. of Tests): Relative Surface Deflation Rate Experiments as Influenced by Unprotected Soil and Gravel Admixture Characteristics.

Test Configuration	Gravel, %, or No. of Layers	No. of Tests for indicated Gravel Size, cm					No. of Tests
		0.00	0.28	0.45-0.67	1.6	3	
Soil-Only ^(a)	-	5	-	-	-	-	5
Single-Size Gravel	10%	-	-	2	-	-	2
	30%	-	1	3	2	1	7
	50%	-	-	2	-	-	2
Well-Graded Gravel							
Mix 1 ^(b)	10%	-	-	1	-	-	1
	30%	-	-	3	-	-	3
	50%	-	-	1	-	-	1
Mix 2 ^(c)	30%	-	-	2	-	-	2
Crushed-Rock Gravel ^(d)	30%	-	-	6	-	-	6
Layered Gravel	1x	-	2	2	2	2	8
	2x	-	2	2	2	2	8
	4x	-	2	2	-	-	4
Total No. of Tests:							49

(a) Two of five soil-only tests were performed during a subsequent series of erosion tests.

(b) Actual average gravel particle size of Mix 1 = 0.57 cm.

(c) Actual average gravel particle size of Mix 2 = 0.45 cm.

(d) Actual average gravel particle size of crushed-rock gravel = 0.64 cm.

only, well-graded gravel, crushed-rock, and gravel layering treatments, both to supply additional degrees of freedom and to compare with soil and gravel admixture results.

The statistical analysis for gravel mass percentage at the 0.67-cm gravel size as well as for Mix 1 may be conducted concurrently or individually as outlined above. It was recognized that the data from several treatments (the soil-only, and two of the 30% gravel treatments) were used more than once in the statistical treatment. Although this could result in some erroneous judgments of statistical significance (i.e., type I errors larger than the nominal $p < 0.05$), the exploratory nature of the study supported the conclusion that the course outlined was best and reduced the chance of failure to measure significant differences between various treatments. As tests performed in different years were potentially affected by surface preparation and measurement technique differences, and because the bare-surface series of tests required more than 1 year of effort, the repeatability of test measurements from one year to another was determined. The effect of year of test on repeatability was evaluated for one comparable treatment between FY 1987 and FY 1988 (1.6 cm at 30%), and the soil-only case between FY 1988 and FY 1989.

A listing of tests is shown in Table 4.2. Five test series are listed, single-size gravel, soil-only, well-graded gravel, crushed-rock gravel, and gravel layer tests. A total of 49 tests was performed; 11 single-size gravel, 5 soil-only, 7 well-graded gravel, 6 crushed-rock gravel, and 20 layered gravel tests. The tests provided data on the influence of the following parameters on relative surface deflation rates: 1) the presence or absence of gravel; 2) gravel particle size; 3) gravel concentration in surface admixtures, by mass; 4) gravel particle size distribution; 5) angularity of gravel particles; and 6) layered gravel.

4.2 APPLIED EROSIVE FORCES: MEAN WIND SPEED, BOUNDARY LAYERS, SURFACE ROUGHNESS, AND FRICTION VELOCITY

Wind forces applied to the surfaces of soil and gravel admixtures in the wind tunnel were characterized to provide a measure of surface shear stresses present during each test, and thus to allow comparison of measured rates of surface deflation. The mean wind speed was measured, and turbulent fluctuations present during tests were characterized. The horizontal profile of wind speed over the test surfaces was measured. The vertical boundary layers occurring over approach, boundary layer, and test surfaces were measured and compared. These measurements provided data from which aerodynamic surface roughness and the surface shear forces (calculated as friction velocity, u^* , see Section 3.2) were calculated.

TABLE 4.2. Bare-Surface Tests Performed to Determine Relative Rates of Surface Deflation Under Controlled Wind Stresses

Test Series	Test ID	Date Started	Gravel Characteristics		
			Size cm	Concentration %	Depth ^(a) of Gravel Layer
Single-Size Gravel	BAR-05	8/24/87	0.67	30	NA ^(b)
	BAR-09	8/26/87	0.67	30	NA
	BAR-10	8/30/87	1.6	30	NA
	BAR-11	9/16/87	0.67	30	NA
	BAR-12	9/25/87	0.67	50	NA
	BAR-13	9/29/87	0.67	50	NA
	BAR-20	8/30/88	0.67	10	NA
	BAR-21	9/1/88	0.67	10	NA
	BAR-22	9/5/88	1.6	30	NA
	BAR-23	9/7/88	0.28	30	NA
	BAR-24	9/9/88	3	30	NA
Soil-Only ^(c)	BAR-25	9/11/88	0	0	NA
	BAR-26	9/13/88	0	0	NA
	BAR-27	9/15/88	0	0	NA
	BAR-63	7/25/89	0	0	NA
	BAR-73	7/26/89	0	0	NA
Well-Graded Gravel ^(d)	BAR-30	5/25/89	0.57	30	NA
	BAR-32	6/1/89	0.45	30	NA
	BAR-33	6/5/89	0.57	50	NA
	BAR-34	6/12/89	0.57	30	NA
	BAR-36	6/16/89	0.57	10	NA
	BAR-38	6/21/89	0.57	30	NA
	BAR-39	6/26/89	0.45	30	NA
Crushed-Rock Gravel ^(e)	BAR-31	5/30/89	0.64	30	NA
	BAR-35	6/14/89	0.64	30	NA
	BAR-37	6/19/89	0.64	30	NA
	BAR-40	6/28/89	0.64	30	NA
	BAR-41	7/5/89	0.64	30	NA
	BAR-42	7/10/89	0.64	30	NA
Layered Gravel	BAR-43	7/12/89	0.28	NA	1x
	BAR-44	7/12/89	0.67	NA	2x
	BAR-45	7/13/89	1.6	NA	1x
	BAR-46	7/13/89	3	NA	2x
	BAR-47	7/13/89	0.67	NA	4x
	BAR-48	7/14/89	1.6	NA	2x
	BAR-49	7/14/89	0.28	NA	2x
	BAR-50	7/14/89	3	NA	1x
	BAR-51	7/17/89	0.67	NA	1x
	BAR-52	7/17/89	0.28	NA	4x
	BAR-53	7/17/89	3	NA	1x
	BAR-54	7/18/89	0.28	NA	2x
	BAR-55	7/18/89	1.6	NA	2x
	BAR-56	7/18/89	0.67	NA	1x
	BAR-57	7/19/89	0.28	NA	4x

TABLE 4.2. (contd)

Test Series	Test ID	Date Started	Gravel Characteristics		
			Size cm	Concentration %	Depth ^(a) of Gravel Layer
Layered Gravel (contd)	BAR-58	7/19/89	0.67	NA	4x
	BAR-59	7/20/89	1.6	NA	1x
	BAR-60	7/20/89	0.28	NA	1x
	BAR-61	7/20/89	0.67	NA	2x
	BAR-62	7/20/89	3	NA	2x

(a) Depth of gravel layer measured as approximate number of times the characteristic dimension of the gravel size (e.g., 1.6 cm @ 2x, packed to a depth of ~3.2 cm above the soil surface).

(b) NA = not applicable.

(c) Tests BAR-63 and BAR-73 were performed during a subsequent series of tests, but provided relevant data and were thus included in the analysis for this study.

(d) Well-graded gravel characteristics: 1) MMD = 0.57 cm; GSD = 1.82 (Mix 1).
2) MMD = 0.45 cm; GSD = 1.46 (Mix 2).

(e) Tests BAR-40, -41, and -42 were special tests performed to determine initial (un-aged) rates of deflation.

Mean wind speed was monitored using a computer data acquisition system connected to a hot film (FY 1987) or to a differential pressure transducer (FY 1988 and FY 1989) as described in Section 3.6.1. Calibrations were performed before and after tests each year. Calibration relationships showed that, although soil particle loading of the HEPA filter bank required occasional adjustment of the wind tunnel fan controller, measurement of wind speed remained accurate during all tests. Calibration relationships are shown in Table 4.3 and relate wind speed referenced to the micromanometer standard to the magnitude of the analog signal received by the computer system from the hot film anemometer or differential pressure transducer. Note the similarity of the relationships between the second two years, when similar instruments were used; the year-to-year variation was about 1% at a wind speed of 20 m/s. Figure 4.1 shows the mean wind speed calibration for FY 1988. Magnitudes of real velocity fluctuations measured in the free stream flow ranged from 0.2 to 0.6% of the mean velocity for wind speeds between 5 and 25 m/s.

Horizontal velocity profiles were measured at an elevation of 28 cm above the test surface (near the vertical wind tunnel centerline) and at wind speeds of 5, 10, 15, 20, and 25 m/s. These results, shown in Figure 4.2, reveal that little variation occurred in wind velocities across the width of the test surfaces. The 51-cm-wide test surfaces were centered in the test section between two flat aluminum spacers, between the 2 and 22 in. positions on the figure, and were therefore not exposed to the turbulent boundary layers existing within 5 cm of the smooth side walls. Although difficult to see clearly in the figure, velocities across the width of the test surfaces ranged from 95 to 102% of the free-stream velocity. The south side of the test section may have averaged wind speeds of as

TABLE 4.3. Calibration Relationships for Mean Wind Speed Measured over Test Surfaces in the Wind Tunnel Test Section. Equation: $U = a \times (HP)^b$, where U = wind speed in m/s, HP = analog signal in volts, and a and b are constant coefficients.

Year	Device	a	b	Coefficient of Correlation
FY 1987	Hot film	9.78×10^{-6}	6.29	≥ 0.995
FY 1988	Diff. press. transducer	15.02	0.494	1.000
FY 1989	Diff. press. transducer	14.93	0.496	1.000

much as 0.5% greater than those at the north side for wind speeds greater than 5 m/s; a difference not thought to be significant. Uncertainty limits shown on the figure include the range of measured velocities at each wind speed and location.

Vertical boundary layers were measured over three surfaces: the flat-plate aluminum (reference) floor of the wind tunnel test section upwind of test and boundary layer surfaces, the PVA-coated boundary layer surfaces immediately upwind of the test surfaces, and various configurations of test surfaces. The importance of these measurements in defining the aerodynamic drag of test surfaces, and the magnitudes of surface shear stresses applied to test surfaces, was described in Section 3.2. From the boundary layer measurements, two wind erosion parameters

FIGURE 4.1. Mean Wind Speed Calibration for FY 1988 Wind Erosion Tests

FIGURE 4.2. Horizontal Velocity Profiles in Free Stream Above Bare-Surface Admixtures During Wind Erosion Tests

were determined--aerodynamic surface roughness, Z_o , and friction velocity, u^* . Variation in results was primarily because of measurement difficulties in defining the exact average local elevation of the rough surfaces that were changing under the influence of wind forces, a condition that worsened with increasing gravel particle size. As measurements were being performed, soil was removed, gravel shifted, and wind flow patterns altered, all of which influenced measurement stability and repeatability. Regardless, measurements were sufficient to quantify surface shear stresses present during the tests.

Surface shear forces were characterized by determining the aerodynamic surface roughness and friction velocity during many tests. Because aerodynamic surface roughness is not equal to an average height of surface elements over some defined datum, but is rather an estimate of the elevation at which mean wind speed approaches zero, it was determined by graphically extrapolating results of boundary layer measurements to the point of zero mean wind speed. The magnitude of surface roughness is constant for a given surface, regardless of reference wind speed over the surface, unless the wind forces alter or smooth the surface (for example, a grass surface is smoothed by wind, and the admixture surfaces were altered by erosion between measurements). The dimension of surface roughness is often about an order of magnitude less than the average height of measured surface objects such as gravel or vegetation. This is because surface objects do not block wind forces completely from the lower regions of the air and surface interface. The second wind erosion

parameter considered, friction velocity--so called because it is defined in terms of length divided by time--was calculated as the square root of the product of the surface shear force divided by the air density [see Equation (3.1)]. The greater the friction velocity, the larger the shear forces that acted to initiate soil particle suspension. Friction velocities, and thus surface shear stresses, were therefore a function of both the magnitude of the wind vector and surface roughness.

Vertical air-flow boundary layers measured over all three types of surfaces are shown in Figures 4.3 through 4.5. Boundary layers were measured over the reference (flat aluminum plate) surface at wind speeds of 2.2, 4.5, 9.0 and 18 m/s. These are shown (Figure 4.3) relative to actual and normalized mean wind speed, and also as the natural log of dimensionless height [$\ln(\text{elevation}/1\text{cm})$] versus mean wind speed. In all cases, mean wind speed referred to the average speed of air in the free stream at an elevation above the influence of the boundary layer. The plot of normalized wind speed shows that a relatively thicker boundary layer existed at the slower wind speeds as the flow contained less momentum to impart to the lower regions of the boundary layer. Because of the very small height (< 0.1 mm) of roughness elements on the reference surface, the dimensionless height plot shows some uncertainty in the value of the ordinate intercept because it was difficult to locate the tip of the pitot-static probe within less than ± 0.1 mm of a known elevation datum during each measurement, especially at higher wind speeds.

Vertical boundary layers were measured over the PVA-coated boundary layer surfaces during all 3 years of testing. Most measurements were made over the weathered 30%, 0.67-cm gravel and soil admixture because it was the surface most often used to create a boundary layer over test surfaces. Boundary layers were measured at wind speeds between 5 and 30 m/s, and were easier to obtain than those over actual test trays as the PVA coating prevented changes in surface morphology during the measurements. A very slight increase (about 1%) in the mean velocity near the top of the boundary layer compared with the free stream velocity was observed and attributed to aerodynamic focusing of the air caused by the formation of the turbulent boundary layer over the boundary layer and test surfaces. A comparison between boundary layers over the 0.67-cm admixture and the soil-only boundary layer surfaces is shown (Figure 4.4). That the gravel admixture surface provided greater drag than the smooth soil-only surface is evidenced by the relatively thicker boundary layers at the selected wind speeds, 12 and 23 m/s. However, differences between the two boundary layers were small compared with the boundary layers existing over the reference surface. This provided evidence that use of the boundary layer surfaces was necessary to avoid unnatural scouring velocities at the leading edge of test trays. However, the use of a single "average" boundary layer surface would probably have been sufficient to form stable boundary layers over test trays of differing composition.

FIGURE 4.3. Boundary Layers over the Reference (Flat Aluminum Plate) Surface. Plots of elevation versus wind speed (U) and normalized wind speed (U_n), and dimensionless elevation versus mean wind speed [$\ln(\text{elevation}/1\text{cm})$ vs. U].

FIGURE 4.4. Boundary Layers over Weathered, PVA-Coated Boundary Layer Surfaces. Results of profiles over soil and 0.67-cm admixture surfaces from FY 1988. Plots of elevation versus wind speed and normalized wind speed, and dimensionless elevation versus mean wind speed [$\ln(\text{elevation}/1\text{cm})$ vs. U].

FIGURE 4.5. Boundary Layers over Test Surfaces (weathered soil and gravel admixture surfaces and single-layered gravel surfaces). Plots of dimensionless elevation versus mean wind speed [$\ln(\text{elevation}/1\text{cm})$ vs. U].

Results of boundary layer measurements over the PVA-coated boundary layer surface consisting of a 30% admixture of 3-cm gravel and soil did not indicate relatively uniform flow patterns in the air flow immediately over the surface. The shape of the boundary layer was greatly influenced by the presence or absence of the large rocks immediately upwind of the location of the pitot-static probe. The range of possible measured surface roughness and friction velocity was therefore relatively large, and was possibly not well represented by the few data obtained during this study.

Measurements of boundary layers over actual test surfaces (Figure 4.5) were limited, as described above, by changes in surface morphology (changes were caused by exposure to wind speeds greater than 10 m/s) during and between pitot-static probe traverses and by variations of flow patterns as influenced by single large gravel particles (greater than about 1 cm). Thus, aerodynamic surface roughness values for the same surface were generally different when measured at 20 m/s than when measured at 10 m/s--because the surface morphology had changed in the interim between measurements at the two wind speeds. One method of obtaining usable data was to neglect data collected at elevations less than the characteristic dimension of the gravel particles, a region where flow patterns were greatly influenced by individual rocks. This was done for the two lowest elevations in several of the data sets. Non-linear lower portions of the boundary layers plotted as $\ln(\text{elevation}/1\text{cm})$ versus mean wind speed reflected flow blockage or channeling and were characteristic of this condition. Measurements were performed over seven of the eight admixture surfaces (no measurements were performed during the single test performed using a 3-cm gravel admixture).

Measurements of boundary layers over test surfaces consisting of layered gravels were more stable than those over soil and gravel admixtures as the surface morphology did not change greatly, and fewer gaps were present between the large-diameter rocks in the 1.6- and 3-cm gravel layers. Results (Figure 4.5) of one set of data for a single gravel layer indicate an increase in surface roughness and friction velocity with increasing gravel size. These results were typical for all layered gravel tests with the qualification that results were increasingly varied as gravel size increased, because of channeling and blockage of the air flow.

A summary of all boundary layer data measured over the various surfaces and calculated wind erosion parameters Z_o and u^* , shown in Table 4.4, indicates that boundary layer surfaces were necessary to develop a boundary layer of reduced-velocity air immediately over the test surfaces. At all wind speeds, conditioned boundary layers were seen to be about 2.5 times thicker over boundary layer and test surfaces than over the reference surface, and provided a measure of the reduction of

TABLE 4.4. Summary of Vertical Air Flow Boundary Layer Profile Measurements Including Wind Erosion Parameters: Aerodynamic Surface Roughness, Z_0 ; and Friction Velocity, u^* . Form of Equation: $\ln(\text{elevation}/1\text{cm}) = b + M(U)$.

Surface	Wind Speed	b	M	Wind Erosion Parameters	
	U, m/s			Zo cm	u* m/s
Reference:					
Flat Al Plate (FY 1987)	2.2	-6.26	3.71	0.0019	0.11
	4.5	-7.22	2.03	0.0007	0.20
	9.0	-8.11	1.104	0.0003	0.36
	18.	-8.37	0.555	0.0002	0.72
Boundary-Layer:					
Soil-only (FY 1988)	12.0	-5.18	0.544	0.0056	0.74
	23.1	-5.02	0.274	0.0066	1.46
	30.0	-4.53	0.200	0.0108	2.00
0.67 cm (FY 1987)	4.85	-3.37	1.120	0.034	0.36
	9.9	-3.13	0.492	0.044	0.81
	14.5	-3.35	0.352	0.035	1.14
	19.6	-3.13	0.255	0.044	1.57
	24.6	-3.26	0.205	0.038	1.95
0.67 cm (FY 1988)	12.1	-2.74	0.343	0.065	1.17
	23.4	-2.63	0.176	0.072	2.27
	29.1	-2.70	0.144	0.067	2.78
0.67 cm (FY 1989)	10.0	-3.48	0.518	0.031	0.77
	19.9	-3.60	0.270	0.027	1.48
3 cm (FY 1988)	9.9	-4.03	0.555	0.018	0.72
	19.4	-3.79	0.277	0.023	1.44
	24.0	-3.66	0.216	0.026	1.85
Admixture Test Surfaces:					
Soil-only (FY 1988)	10.0	-5.70	0.691	0.0033	0.58
	19.2	-5.48	0.369	0.0042	1.09
0.28 cm (FY 1988)	10.4	-3.36	0.488	0.035	0.82
	20.0	-2.79	0.227	0.061	1.77
0.67 cm (FY 1987)	10.2	-3.00	0.482	0.050	0.83
1.6 cm (FY 1987) ^(a)	10.1	-1.5	0.334	0.2	1.20
Mix 2 (FY 1989) ^(b)	10.2	-3.47	0.508	0.031	0.79
	20.2	-2.06	0.189	0.13	2.12
Mix 1 (FY 1989) ^(b)	10.2	-4.12	0.575	0.016	0.70
	20.5	-3.42	0.268	0.033	1.50
Crushed-Rock (FY 1989) ^(b)	10.3	-4.46	0.595	0.012	0.67
	19.8	-2.78	0.233	0.062	1.72

TABLE 4.4 (contd)

Surface	Wind Speed	b	M	Wind Erosion Parameters	
	U, m/s			Zo cm	u* m/s
<u>Layered Gravels (FY 1989):</u>					
1x 0.28 cm(c)	20.1	-2.78	0.233	0.062	1.72
	20.1	-3.65	0.279	0.026	1.43
2x 0.28 cm	20.1	-2.74	0.230	0.065	1.74
	20.1	-3.75	0.285	0.024	1.40
4x 0.28 cm	20.2	-2.80	0.227	0.061	1.76
	20.1	-3.17	0.246	0.042	1.63
1x 0.67 cm	20.0	-3.04	0.248	0.048	1.61
	19.9	-2.33	0.210	0.097	1.90
2x 0.67 cm	20.2	-2.16	0.200	0.115	2.00
	20.3	-3.34	0.253	0.035	1.58
4x 0.67 cm	20.0	-1.91	0.182	0.15	2.20
	20.2	-1.86	0.177	0.16	2.26
1x 1.6 cm	20.0	-1.76	0.180	0.17	2.22
	20.1	-1.40	0.165	0.25	2.42
2x 1.6 cm	20.0	-1.96	0.188	0.14	2.13
	20.2	-3.33	0.267	0.036	1.50
1x 3 cm	20.0	-2.70	0.224	0.067	1.79
	20.4	-0.73	0.140	0.48	2.86
2x 3 cm	20.2	-0.72	0.122	0.49	3.28
	20.2	-3.33	0.262	0.036	1.53

(a) Average results listed (range of Zo = 0.10 to 0.37 cm, range of u* = 1.0 to 1.4 m/s).

(b) Characteristic gravel sizes for well-graded and crushed-rock gravels: 0.45 cm (Mix 2), 0.57 cm (Mix 1), and 0.64 cm (crushed-rock).

(c) Gravel layers were one (1x), two (2x), and four (4x) times the characteristic dimension of the gravel particles as described in Section 4.1.

wind velocities immediately over the surfaces. Although velocities were reduced, the force of the wind on the tested surfaces was greater than that on the reference surface because of the large surface area and rough morphology of the boundary layer and test surfaces; friction velocities were about two times greater, indicating about four times more erosive stress on the boundary layer and test surfaces than on the reference surface [see Equation (3.1), Section 3.2].

The influence of mean wind speed and surface characteristics on wind erosion parameters (derived from data presented in Table 4.4) is shown in Figure 4.6. Aerodynamic roughness heights generally increased with increasing size of gravel present in the admixtures. The Zo of the reference surface was about $8 \pm 8 \mu\text{m}$. Over boundary layer surfaces, Zo increased from $0.0077 \pm 0.0028 \text{ cm}$

FIGURE 4.6. Wind Erosion Parameters, Aerodynamic Surface Roughness Height, Z_o , and Friction Velocity, u^* , as Functions of Mean Wind Speed and Diameter of Roughness Elements (Al plate roughness, sand in soil-only, and gravels mixed at a concentration of ~ 30%).

over the soil surface to 0.046 ± 0.016 cm over the 0.67-cm gravel admixture surface. Although Z_0 for the 3-cm gravel boundary layer surface at 0.022 ± 0.004 cm was less than that for the 0.67-cm gravel surface, this occurrence was attributed to the location of the pitot-static probe between and not immediately downwind of the 3 cm rocks. Roughness heights over tested surfaces increased as gravel size increased (Figure 4.6), but variability also increased as the larger rocks caused greater flow deflections, channeling, and blockages. Surface roughness remained roughly constant as gravel layers were increased from 1 to 2, and (for 0.28- and 0.67-cm gravels) to four times the characteristic dimension of the gravel particles.

Friction velocities were seen to be linearly related to mean wind speed. However, although little variation occurred for the relatively smooth reference and soil surfaces, data were scattered for gravel admixture and layered gravel surfaces for reasons identified above. Between 5 and 25 m/s, the friction velocity over the reference surface was estimated to increase from 0.20 to 1.0 m/s (Figure 4.6), the greater number based on a linear extrapolation of data for wind speed greater than 18 m/s. The friction velocity over boundary layer and test soil surfaces was roughly 1.8 times greater, increasing from 0.21 to 1.6 m/s as wind speed increased from 5 to 25 m/s. Friction velocities over admixture and gravel layer surfaces were greater than those over soil surfaces, and two to three times greater than those over the reference surface. Thus, surface shear stresses ranged from four to nine times greater than those over the reference surface.

Friction velocities were also seen to increase as surface roughness increased (Figure 4.6). At a mean wind speed of 20 m/s, friction velocity increased from 1.6 to 2.4 m/s as gravel size increased from 0.28 to 3 cm, a trend that was also representative of the small roughness elements present in the soil-only and reference surfaces. Limits of uncertainty shown on the plot include the range of measured friction velocities at each gravel size and a mean wind speed of 20 m/s; increasing uncertainty with increasing gravel size was similar to that described above for boundary layers and roughness heights. The increase revealed that, at a free stream wind speed of 20 m/s, greater surface shear stresses were developed over surfaces having larger gravel sizes. A lesser increase in friction velocity with increasing gravel size was observed at a mean wind speed of 10 m/s; however, as the number of data were limited, uncertainty limits could not be estimated.

An upper wind speed range for wind tunnel tests of 25 m/s was identified in Section 3.2 for wind tunnel tests representative of the 200 Area Plateau at the Hanford Site. At this wind speed, friction velocities over test surfaces, based on linear extrapolation of data collected during this study, would range between about 1.6 and 2.6 m/s. Assuming an air density of 1.2 g/m^3 , this range of friction velocities would provide surface shear stresses ranging from 0.003 to 0.008 N/m^2 .

4.3 SOIL MOISTURE CONTENT

Although soil moisture content was not a test parameter in the present study, measurements were required both because SMC is an important soil characteristic influencing erodibility, and to provide data for determining the fraction of measured surface mass loss caused by evaporation of moisture rather than erosion of particulate matter. As described in Section 3.6.7, SMC was defined as the moisture content of the non-gravel fraction of the admixtures. In addition, measurements of the evaporation rate from surrogate surfaces and from a compacted soil surface were made to investigate the influence of wind speed on evaporation potential. Tests are planned for subsequent years to test the influence of SMC on erosion from selected gravel admixtures.

Results of destructive sampling measurements of SMC are shown in Table 4.5. Pre- and post-test measurements were made of bulk SMC, and post-test measurements were made of surface SMC. Post-test bulk SMC measurements from tests 40, 41, and 42 were significantly greater than average; this was thought to have been the result of shorter test durations (less time available for evaporation to occur). Because all tests were of varying durations, and exposed to varying combinations of wind stresses, evaporation potential was not uniform. The average post-test bulk SMC, however, for all tests except 22 and 30, was $73 \pm 9\%$ ($n = 25$, uncertainty = 1 standard deviation) of the average pre-test bulk SMC. Results of FY 1987 post-test surface SMC measurements are not believed to reflect actual conditions as they were made after a period of time had elapsed following the final application of erosive forces. Again, except for tests 22 and 30, the post-test surface SMC for FY 1988 and FY 1989 was $66 \pm 8\%$ ($n = 16$) of the post-test bulk SMC, and about $50 \pm 8\%$ ($n = 16$) of the pre-test bulk SMC. The anomalous measured increase in SMC during test 22 was not credible and was attributed to an undetermined gross measurement error. The SMC of the compacted soil beneath the gravel in the layered gravel tests was initially about 4%; post-test SMC measurements were not made, but were not anticipated to change greatly during the 2-hr tests.

In addition to destructive SMC samples, which were obtained during each year's testing, most FY 1988 tests also included measurements of SMC using sets of two vertical miniature conductivity probes. Although a probe was calibrated before the devices were used in wind erosion tests, the combined data from all probes after completion of the FY 1988 tests revealed that the calibration was not uniform from probe to probe and test to test. The original calibration relationship was linear between 1 and 8% SMC and was $SMC = 9.44 - 0.608 * V$ ($R^2 = 0.99$). In the equation, SMC = soil moisture content in %, and V = the average differential voltage across four pairs of adjacent electrodes. Comparison with calibration data obtained during the tests revealed that the

TABLE 4.5. Soil Moisture Contents of Soil Fraction of Test Surfaces

Test	Fiscal Year	Surface	Soil Moisture Content, %		
			Bulk ^(a) Pre-Test	Bulk Post-Test	Surface ^(b) Post-Test
25	1988	Soil-Only	4.85 ± 0.01 ^(c)	3.82 ± 0.04 ^(c)	2.13 ± 0.15 ^(c)
26	1988	Soil-Only	4.85 ± 0.01	3.75 ± 0.05	ND
27	1988	Soil-Only	4.85 ± 0.01	3.64 ± 0.01	ND
23	1988	30%, 0.28 cm	5.33 ± 0.08	3.78 ± 0.20	2.43 ± 0.29
32	1989	30%, Mix 2	4.05 ± 0.14	3.04 ± 0.02	2.18 ± 0.12
39	1989	30%, Mix 2	3.97 ± 0.34	2.70 ± 0.12	1.92 ± 0.07
36	1989	10%, Mix 1	3.90 ± 0.12	2.66 ± 0.05	1.92
30	1989	30%, Mix 1	4.11 ± 0.04	2.23 ± 0.41	2.10 ± 0.03
34	1989	30%, Mix 1	4.02 ± 0.32	2.79 ± 0.12	2.15 ± 0.02
38	1989	30%, Mix 1	4.27 ± 0.13	2.68 ± 0.15	2.06 ± 0.08
33	1989	50%, Mix 1	4.33 ± 0.16	3.58 ± 0.05	1.97
31	1989	30%, Crushed	3.61 ± 0.18	2.79 ± 0.14	1.86 ± 0.05
35	1989	30%, Crushed	4.07 ± 0.07	3.02 ± 0.01	1.89
37	1989	30%, Crushed	4.10 ± 0.02	2.94 ± 0.08	1.85 ± 0.02
40	1989	30%, Crushed	3.70 ± 0.07	3.07 ± 0.08	2.26 ± 0.06
41	1989	30%, Crushed	3.79 ± 0.04	3.18 ± 0.03	2.03 ± 0.03
42	1989	30%, Crushed	3.56 ± 0.07	3.21 ± 0.05	2.06 ± 0.01
20	1988	10%, 0.67 cm	4.83 ± 0.08	4.03 ± 0.53	1.91 ± 0.48
21	1988	10%, 0.67 cm	4.83 ± 0.08	3.86 ± 0.01	2.58 ± 0.02
5	1987	30%, 0.67 cm	2.69 ± 0.08	2.12 ± 0.01	1.96 ± 0.01
9	1987	30%, 0.67 cm	4.27 ± 0.17	2.38 ± 0.09	2.38 ± 0.16
11	1987	30%, 0.67 cm	3.48	2.24 ± 0.08	2.28 ± 0.07
12	1987	50%, 0.67 cm	6.09 ± 0.66	3.80 ± 0.23	5.25 ± 0.96
13	1987	50%, 0.67 cm	6.09 ± 0.66	3.86 ± 0.02	3.67 ± 0.11
10	1987	30%, 1.6 cm	6.12 ± 0.09	3.69 ± 0.38	2.18 ± 0.18
22	1988	30%, 1.6 cm	4.94 ± 0.12	5.13 ± 0.62	7.09 ± 0.12
24	1988	30%, 3 cm	5.60 ± 0.43	4.07 ± 0.20	ND
43-62	1989	Layered Gravel	~4.0	ND	ND

(a) SMC averaged over depth of surface (5 cm pre-test).

(b) SMC of top ~ 1 cm of surface post-test.

(c) Measurement uncertainties equal the range of two or three measurements. The lack of uncertainty values for four cases was because of a lack of replicate measurements or presumed measurement error.

ND = no data.

calibration under-predicted actual SMC by about 1% of SMC, and that the uncertainty in the result was about ±1%.

Use of the probes did provide results on the vertical distribution of soil moisture within the 5-cm-deep surface layer. For example, when water was sprayed on top of dry (1.4% SMC) compacted soil and sealed with a lid to prevent evaporation, the vertical profile of soil moisture was

found to be related to the amount of water added. When the amount of water added was sufficient to bring the average SMC of the surface to 3%, nearly all of the added water was incorporated into the top 2 cm of the surface. When water was added to 4%, water remained in the top 3 cm of the surface. At 6%, most of the water was stored between depths of 0 and 4 cm, with the wettest soil located at 1 to 3 cm. At 8%, water penetrated to the bottom of the surface, and the wettest soil was located at all depths below 2 cm. In all cases, several hours were required before the SMC probes indicated a stable soil moisture profile had developed.

The SMC probes could be used to obtain SMC profiles in the surface layer; however, obtaining destructive samples of co-located exposed surfaces should provide a better method of tracking surface SMC readings for future tests. The use of a co-located surface, perhaps located immediately downwind of the test surface would allow periodic sampling to be performed without disturbing the actual test surface. The destructive method would have the advantage of being simpler, would not require a calibration, and could provide SMC data in the top few millimeters of surface, rather than in the top 1 cm.

In addition to destructive sampling and the use of SMC probes for measuring SMC, another set of measurements was made to provide indirect and approximate information on the influence of wind speed on evaporation potential. Surrogate surfaces (sponges) were tested to provide an evaporating surface that did not lose solid mass during the tests. In addition, soil surfaces, compacted as during the wind erosion tests, were also tested at a wind speed less than the threshold velocity of particle suspension to provide a point of comparison. All tests were performed at temperatures of 21 to 22° C and relative humidities of 30 to 34%. Results of the surrogate surface measurements showed a linear increase in evaporative potential with increasing wind speed between 0 and 20 m/s. The following relationship was determined: $ER = 1.6 + 0.84 * U$ ($R^2 = 0.999$), ER = evaporation potential in g/hr, and U = mean wind speed in m/s. Next, the evaporation rate from compacted soil surfaces was measured at a mean wind speed of 2.5 m/s over a period of 15 hr. The initial SMC was 4.2%. The result was $ER = 0.560 * t^{-0.509}$ ($R^2 = 0.985$), ER = evaporation rate potential in g/hr, and t = drying time in hr. Provided that a similar linear relationship of evaporation potential versus wind speed exists for soil as for the surrogate surfaces, the rate of evaporation from the 2310 cm² soil and admixture surfaces tested in the wind tunnel may range from 30 to 5 g/hr at 10 m/s, and from 90 to 15 g/hr at 20 m/s, as the exposed surfaces gradual dry between 1 and 30 hr of exposure. A humidity-driven force model and consideration of soil moisture on a percentage saturation basis could potentially provide better evaporation rate data than this approximate method.

4.4 AIRBORNE PARTICLE SAMPLING

Two methods were used to measure surface deflation during wind tunnel tests, sampling the suspended dust and measuring the change in the gross mass of test surfaces. Both methods were used extensively in FY 1987 to determine their relative merits and, if both proved sufficient, to provide independent measures of deflation rates. The use of gross surface mass measurements periodically during tests, either using a mass balance under the test surfaces in the wind tunnel, or removing the surfaces periodically for measurement, proved superior to measurement of suspended particulate matter primarily for reasons of measurement repeatability and ease. Difficulties with measurement repeatability were mainly the result of an inability to sample 100% of the airborne particulate matter suspended from the surfaces. Improvement of the aerosol method would require a very large air sampler to collect particulate matter within the entire trailing edge boundary layer as described in Section 3.6.5.

Aerosol sampling was performed to obtain the mass flux of dry particulate matter from the test surfaces. Because only a small fraction of the total dust aerosol could be sampled, measurements were performed at several locations so that a vertical profile of the dust aerosol concentration could be determined and estimations of horizontal flux could be made. Non-uniform distributions of particulate matter concentration with height, influenced by the intermittent nature of erosion events and the very large variation in size of suspended particles, resulted in large uncertainty in the estimated particle suspension (surface deflation) rates.

4.4.1 Fluorescent Tracer

Use of the tracer in FY 1987 proved valuable during aerosol probe calibration tests, but did not increase the sensitivity of the gravimetric analysis because of resolution limitations of the only available fluorometers; the procedure was not repeated in subsequent years. Validation of the bulk mass measurement procedure during FY 1987 also contributed to a lesser need to rely on aerosol measurements and thus a lesser need to use a fluorescent tracer. Tracer methods may yet prove valuable for future planned tests of saltating sand particles and surface crusts.

A calibration of fluorescence versus particulate mass collected on glass fiber filter substrate revealed that the fluorescent tracer method was useful as an indicator of soil particle mass collected, but that no increase in resolution over the gravimetric method could be obtained (the gravimetric method was useful for masses greater than 0.05 mg). The tracer calibration is shown in Figure 4.7. A significant degree of scatter in the calibration data set indicated that inhomogeneities in the tracer-soil mix may have prevented uniform suspension of soil and dye particles. It is also likely that the

FIGURE 4.7. Calibration of Fluorescent Tracer Versus Mass of Dry Particulate Matter Collected in Aerosol Samples

dye did not mix uniformly within soil clods. An increase of resolution to the 0.005 mg level would require an increased mix concentration from one part dye per 10,000 parts soil, to one part dye per 1000 parts soil, mixing the dye and soil under desiccated conditions and then slowly adding water, or improved fluorimetry.

4.4.2 Aerosol Sampling Probe Losses

Knowledge of probe sampling effectiveness, the percentage of each aerosol sample lost by deposition to the inner walls of the sampling nozzles, was important in determining a correction factor to be applied to the gravimetric analysis of aerosol probe filter samples. Two mechanisms were thought to be primarily responsible for sampling probe losses. Because samples were obtained in the turbulent flow of the boundary layer over test surfaces, turbulence would likely bring some particles into contact with sample probe walls. Also, because of the large size of the soil particles suspended and sampled, sedimentation to the bottom of the 10.0-cm-long sampling nozzles was likely, especially during sampling at the 5 m/s wind speed. Both probe loss mechanisms were influenced by sample flow rate and mean approach wind speed.

Aerosol sampling probe losses were determined by rinsing selected nozzles after sampling and analyzing the resulting solutions fluoroscopically. By comparing them with the fluorometer calibration relationship, estimates were made of the mass of soil lost to the walls of the sampling

probes. Probe loss was determined as the ratio of the mass collected in the sample probe divided by the sum of the mass collected in the sample probe and the soil mass collected on the probe's filter. Measurements were repeated twice for samples at a mean wind speed of 5 m/s, four times at 10 m/s, and twelve times at 20 m/s. Correction factors were then determined as the inverse of unity less the probe loss decimal percentage, and applied to all aerosol probe filter data collected at each respective wind speed. Probe losses were $40 \pm 6\%$ at 5 m/s (11 mph), $14 \pm 12\%$ at 10 m/s (22 mph), and $2.6 \pm 1.5\%$ at 20 m/s (45 mph). The decrease in probe losses with increasing wind speed was attributed to decreased particle residence time in the sampling nozzle and resuspension of deposited particles. Correction factors applied to all resuspension data were 1.67 ± 0.16 at 5 m/s, 1.17 ± 0.16 at 10 m/s, and 1.027 ± 0.016 at 20 m/s. Uncertainty values included the range of all data.

4.4.3 Suspended Particle Concentration Profiles

Isokinetic sampling probes were generally positioned at an elevation of 1.9 cm above the test surface. This was done to provide relative information on soil particle suspension rates for different test surfaces, wind speeds, and exposure durations. Additional data were obtained, however, at other elevations above the test surfaces. These data were used to determine soil particle aerosol mass concentration profiles above the test surfaces. Results of these measurements revealed differences between the two tested wind speeds of 10 and 20 m/s.

Normalized soil particle concentration profiles are shown in Figure 4.8. Although not shown in the figure, other measurements revealed that very little particulate matter was present in the free stream above the air-flow boundary layers, much less than that collected at any elevation within the air-flow boundary layer. Elevation uncertainty limits were about ± 0.4 cm, and normalized aerosol mass concentration uncertainty limits include the standard deviations of similar measurements. All aerosol concentration data were normalized about the values measured at a reference elevation of 1.9 cm. Normalized concentration results obtained in FY 1988 were consistently greater than those obtained in FY 1987, possibly because of improved sampling techniques. Four or five measurements at each elevation were performed in FY 1987, and 13 or 14 in FY 1988. The aerosol mass concentration of soil particles was seen to decrease with increasing elevation for both tested wind speeds, 10 and 20 m/s, but was seen to decrease to a greater extent at 20 m/s. Although the concentration at 4.45 cm was about one-half of that at 1.9 cm at 10 m/s, it was one-fifth to one-tenth that at the reference elevation at 20 m/s. Although the results at 10 m/s indicated that a relatively blunt aerosol concentration profile existed over the surfaces, the degree of variation in data obtained at 10 m/s was great and the average results do not accurately represent specific actual soil particle concentration profiles. Because the degree of variability in the results at 20 m/s was much less, an

FIGURE 4.8. Vertical Aerosol Soil Mass Concentration Profiles over Test Surfaces at 10 and 20 m/s. Normalized for Concentration at an elevation of 1.9 cm.

exponential decrease in aerosol mass concentration with increasing elevation over the surfaces was evident, and results indicated that most air-suspended particulate mass was transported within the lower regions of the air-flow boundary layer. Variability in the results, in decreasing order of perceived impact, was attributed to the unsteady soil mass flux from test surfaces, variations in test surface configuration, the changing (not measured) size distribution of particles transported by suspension, saltation, and creep at specific periods during the tests, and unknown sampling errors.

4.5 SURFACE DEFLATION RATE CONSIDERATIONS

Considerations necessary before performing deflation rate comparisons included tabulating measured surface mass loss information, performing a comparison of surface mass loss and aerosol

probe results, and identifying the influences of evaporation of soil moisture and wind speed on deflation rates. In addition, the repeatability of surface deflation measurements, both from test to test and from year to year, were determined.

4.5.1 Surface Mass Loss

A list of surface mass loss measurements for each of the 50 tests discussed in this report are shown in Appendix A. Tests are ordered numerically, in the order they were performed. The first six columns of the tables in the appendix show the test identification number, the measured wind speed, the exposure duration, the time of aging during the test, the measured surface mass change, and the calculated total deflation rate. The time of aging was determined as the time of continuous exposure to a single wind speed. The change in surface mass included suspended soil particles, evaporated soil moisture, and occasionally gravel that was blown off the surface. Total surface deflation, in $\text{g}/(\text{m}^2\text{-s})$, was calculated as the surface mass loss divided by the product of the surface area and the exposure duration.

The seventh through ninth columns in the tables in the appendix provide a location for determining the fraction of the surface mass loss that was soil particulate mass. This information was determined from estimates of the evaporation rates that existed during tests 20 through 27, and tests 83 and 87. Next, the dry mass rate of deflation was calculated using a procedure similar to that for the total deflation rate calculations. The significance of these results is discussed in Section 4.5.3.

The final three columns in the tables in the appendix show, where possible to calculate, total and dry mass deflation rates corrected for wind speed. Because deflation rates depended strongly on wind speed, corrections were applied to rates measured at wind speeds that deviated from the target values, as described in Section 4.5.4.

4.5.2 Comparison of Aerosol and Surface Mass Loss Results

Although experience gained throughout the study indicated that measuring surface deflation rates by massing the test surface was preferred to measuring the concentration of suspended soil particles at the downwind edge of the test surfaces, a comparison was made to determine whether a small number of sharp-edged isokinetic sampling nozzles could provide information relative to the actual loss of mass from test surfaces. The mass lost by test surfaces was compared with the mass collected by aerosol sampling nozzles for both FY 1987 and FY 1988 data. Figure 4.9 shows the FY 1988 data. For wind speeds of 15, 20, and 25 m/s, a relationship was evident between mass

FIGURE 4.9. Comparison of Surface Mass Loss Measurements with Concurrent Isokinetic Aerosol Mass Samples. Data obtained during FY 1988 at an aerosol sampling elevation of 1.9 cm.

collected in aerosol sampling nozzles and mass loss from exposed surfaces. The relationship was determined to be $AS = 3.82 * (SM)^{0.925}$ ($R^2 = 0.88$), where AS = the mass in mg collected in the isokinetic aerosol sample, and SM = the mass in g lost by the exposed surface. However, for the 10 m/s case, no such relationship was apparent. Presuming no great difference in the vertical distribution of soil particle concentration above the test surfaces over the range of wind speeds, one would expect that the relationship between the aerosol samples and the surface mass loss to be similar for each wind speed case. Should the vertical distribution of soil particles be different at one or more wind speeds, then the relationship between the two measurement methods should still exist, but with a vertical offset (on the plot) between the two cases.

It is interesting to note that Ligothe (1988) reported a relationship between the two measurement techniques existed, based on a preliminary analysis of the FY 1987 data. The relationship at the 20 m/s case was found to be $AS = 3.48 * (SM)^{1.07}$ ($R^2 = 0.97$), that at 10 m/s was $AS = 0.146 * (SM)^{0.884}$ ($R^2 = 0.77$). The relationship for the 10 m/s case was offset about 50 times less than that for the 20 m/s case. Although the relationship for the 20 m/s case is similar to that obtained in FY 1988, it was clear that the weaker relationship at the 10 m/s case was based on too few data.

The lack of a relationship between the two procedures for the 10 m/s case provided a strong indication that a condition other than the possible difference in the vertical distribution of soil particles was influencing the results. One difference between the two measurement techniques was that the surface mass loss measured during each exposure included both dry soil particle mass and evaporation and suspension of soil moisture, while the aerosol sampling method collected only the dry fraction of the suspended material--the volatile fraction of the sample being lost as the sample was filtered from the air stream. As discussed in Section 4.3 and below, mass lost from exposed surfaces during tests at wind speeds equal to or greater than 15 m/s only rarely included a significant ($> 10\%$) fraction of soil moisture. On the other hand, large fractions (20 to 100%) of the mass lost from exposed surfaces at the slower wind speeds was soil moisture. Assuming that if the aerosol data were plotted against the dry fraction of the surface mass loss, the result would be similar to the relationship derived for the faster wind speed cases, the data set shown in Figure 4.9 can be used to estimate the percentage of the surface mass loss for each 10 m/s sample that would have been actually dry soil particle mass, the remainder being soil moisture. Extrapolation of the data set indicated that the range of dry soil particulate mass in the 10 m/s samples ranged from about 0 to 80%, with an average of 40 samples being $10 \pm 15\%$. It must be noted, however, that because of potential differences in the vertical distribution of soil particle mass above the trailing edge of the exposed trays between the 10 m/s and the faster wind speed cases, no certainty exists that the relationship between the aerosol and surface samples for the 10 m/s case would be similar to that for the faster wind speed cases.

4.5.3 Influence of Soil Moisture on Deflation

Although limited by an uncertain calibration (see Section 4.3), an effort was made to estimate the rate of evaporation that occurred during the individual portions of each wind erosion test performed with the SMC probes. These tests included 7 of the 8 tests performed in FY 1988. Test exposures were identified by wind speed as slow (10 m/s) and fast (15 to 25 m/s), and average rates of soil moisture loss were determined for each period. Although the potential for evaporation was greater during the fast wind speed portions of the tests because of the greater drying capacity of the wind, evaporation potential was also high during the slow wind speed portions because the 10 m/s exposures were performed near the beginning of the tests when the admixtures were still near to the original SMC. Tests of admixture surfaces averaged soil moisture loss rates of 5 ± 3 g/hr during the slow wind speed periods, and 13 ± 4 g/hr during the fast wind speed periods. Tests of soil-only surfaces revealed greater loss rates for soil moisture, perhaps because the surfaces were not protected from evaporation by partial gravel covers. During the slow wind speed period, the average rate of soil moisture loss from soil-only surfaces was 8 ± 6 g/hr, and during the fast wind speed period, the

rate was 27 ± 19 g/hr. That the rates were not constant, but started greater and decreased as the exposed surfaces dried, was recognized. However, no suitable method of estimating the rates as a function of time throughout each test was found given the limitations of the data.

Rates of soil moisture evaporation were also possible to estimate for two additional tests because of special evaporation measurements made periodically during the series of wind erosion exposures. These tests, 83 and 87, were replicate tests of the 30% 0.28-cm admixture case. These results are shown in the last table in the Appendix. Tests 83 and 87 differed from the tests performed in FY 1988 in that they were exposed only to 20 m/s, the exposed surface area was 2580 cm² rather than 2310 cm², the admixtures were prepared in 2-cm-deep trays rather than 5-cm-deep trays, and the initial SMCs were about 3.2% rather than 5.3%. The difference in SMC was less than the comparison of pre-test values indicated, however, because test 23 included about 24 hr of exposure to slow wind speeds before the 20 m/s exposures, which allowed the moist surface to dry, whereas exposures at 20 m/s were initiated immediately at the start of the replicate tests. The evaporation rate was estimated to decrease from 60 g/hr initially, to 1 g/hr at the end of test 83, as the surface eroded and gradually dried. During test 87, the evaporation rate was estimated to decrease from 100 to 1 g/hr.

The estimates of soil moisture loss rates were used to investigate the percentage contribution of water to the total mass loss measured from the surfaces during wind erosion tests. Results were similar for all tests with the exception of the fast wind speed case of test 23 and its two replicates, 83 and 87. The average dry particulate mass fraction of surface mass loss measurements during the slow wind speed portions of the FY 1988 tests was $27 \pm 12\%$, indicating that most of the mass loss measured was actually because of loss of soil moisture. Thus, measured total deflation rates did not accurately represent loss of dry soil mass. In contrast, the average dry particulate mass fraction of surface mass loss measurements made during the fast wind speed portions of the FY 1988 tests, including both soil-only and admixture surfaces, was $97.7 \pm 0.8\%$, indicating that nearly all the mass loss measured was actually because of loss of soil particles rather than soil moisture.

One test, test 23, was excluded from the fast wind speed results for FY 1988. This was because 12 of 25 measurements indicated a dry soil mass content of less than 85%, a value less than the single lowest value measured during the other seven tests. Further analysis of the data indicated that the reason for the discrepancy was that the rate at which the surface was deflating was very slow; it was about 10 times less than the slowest rates achieved by the other surfaces. Thus, because soil erosion had been greatly reduced, the rate of evaporation constituted a significant fraction of the total measured mass loss. Most of these measurements indicated that water loss included about one-

half to one-quarter of the total surface mass loss; however, during 2 of the 12 measurements, the estimated rate of soil moisture loss approximately equaled the total mass lost from the surface. The overall average dry particulate mass fraction of the surface mass loss measurements for test 23 was $78.8 \pm 26.9\%$. Loss of soil moisture influenced the two replicate tests to a lesser degree, although loss of soil moisture was again a greater percentage of the total mass loss than from other admixture surfaces, perhaps because their initial SMCs were less than that of test 23. The average dry particulate mass fractions of the surface mass loss measurements during the replicate tests were $89.1 \pm 9.4\%$ (test 83) and $92.0 \pm 5.3\%$ (test 87).

In summary, although direct measurements were not made of the contribution of soil moisture to surface mass loss measured during the wind erosion tests, indirect measurements and estimates from available data indicated that, with the exception of the 30% 0.28-cm test case, loss of soil moisture represented a significant portion of the mass loss during the slow wind speed tests (10 m/s), but did not significantly affect measurements made during the fast wind speed exposures (15-25 m/s). Based on two uncertain methods, the fraction of surface mass loss consisting of dry soil particles during the 10 m/s tests in FY 1988 was estimated to be $10 \pm 15\%$ using extrapolation of the data in Figure 4.9, or $27 \pm 12\%$ using the SMC probe data. It is not inconceivable that the total deflation rate results for 10 m/s exposures were therefore 4 to 10 times greater than the actual dry soil particle deflation rates. In contrast, the fraction of surface mass loss consisting of dry soil particles during the fast wind speed tests (15-25 m/s) was found to be $97.7 \pm 0.8\%$, indicating that the measured, or total, deflation rate was essentially equal to the dry soil particle deflation rate. Comparison of the deflation rate results between the various exposed surfaces is discussed in the following sections, and the total (including both dry soil particle mass and soil moisture) and the dry (soil particle mass only, excluding soil moisture) deflation rates were considered where appropriate.

4.5.4 Influence of Wind Speed on Surface Deflation

In addition to evaporation of soil moisture, small differences in the mean wind speed influenced deflation rate measurements. Because rate of deflation depends strongly on wind speed, even minor differences in wind speed from test to test were thought to be a source of possible interference in the comparison of measured rates of deflation data. This dependence on wind speed is limited to a wind speed range between the threshold velocity of erosion and an upper limit defined by the modulation of wind speed in the boundary layer by momentum transfer to concentrated suspended soil particles, a range that includes most wind events greater than about 5 to 10 m/s in the field. To quantify the influence of wind speed on deflation, two data sets were generated, one for soil-only surfaces and one for a variety of admixture surfaces, to provide information on the

influence of wind speed on rate of deflation. Criteria for selection included similar exposure histories, pre-test weathering, and especially, duration of exposure to wind speeds.

Rate of deflation was found to be strongly influenced by wind speed. As shown in Figure 4.10, the dependence of rate of deflation on wind speed was found for both soil-only and admixture surfaces to be an exponential function. The influence of the gravel admixtures, consisting of gravel sizes between 0.28 and 0.67 cm, compared with the soil-only surfaces, is evident in the figure as the rate of deflation from admixture surfaces ranged from about 10 to 20 times less than that from soil-only surfaces. The relationships between deflation rate and wind speed were $DR = 0.0112 * 10^{(0.183*U)}$ ($R^2 = 0.999$) for the soil-only surfaces and $DR = 0.00321 * 10^{(0.150*U)}$ ($R^2 = 0.999$) for the admixture surfaces, where DR = deflation rate in $g/(m^2-s)$, and U = mean wind speed in m/s . The dependence on wind speed is seen in the coefficient of the exponent and is very similar for both types of surfaces. That the coefficient for the soil-only surfaces is about 20% greater than that for the admixture surfaces may, however, be an indication that gravel admixtures not only decrease rate of deflation, but also decrease the dependence of deflation rate on wind speed.

The influence of wind speed on rate of deflation was determined for a wind speed range of about 10 to 25 m/s . At slower wind speeds, rate of deflation was not anticipated to follow the determined relationships at wind speeds less than the static threshold velocity of erosion, estimated to be about 7 or 8 m/s in the wind tunnel. For the admixture surfaces, the relationship appeared to hold to 25.5 m/s , the fastest wind speed tested. Data obtained from the soil-only surfaces at 25 m/s , however, indicated that the rate of deflation did not increase at the rate predicted by the relationship. The soil-only relationship was determined only from data obtained at 10 to 20 m/s , in part because the 2-min interval used at the other wind speeds was sufficient to cause the surfaces exposed to 25 m/s to fail (surfaces were considered failed when the leading or trailing edges of the supporting tray were exposed because of excessive deflation). The rate of deflation was seen to decrease rapidly during the second minute of exposure at 25 m/s , after the leading and trailing tray rim edges were exposed, and thus, subsequent exposures were only 1 min in duration. Comparison of data obtained during different exposure periods, however, was difficult because deflation rate was not linearly related to time of exposure. For these reasons, the 2-min deflation rates at 25 m/s for the soil-only surfaces were estimated from the 1-min exposures and plotted on the figure separately.

Although estimated from the 1-min exposure data, the plotted (Figure 4.10) 2-min deflation rates from the soil-only surfaces at 25 m/s were seen to be more than 2 times less than that predicted by the relationship determined from data at wind speeds of 10 to 20 m/s . This could not be attributed to the measured results, or to the procedure used to estimate the 2 min deflation rates. Rather, it was

FIGURE 4.10. Rate of Deflation Versus Mean Wind Speed for Soil-Only and Admixture Surfaces Containing 0.28- to 0.67-cm Gravel Sizes

possible that the less-than-anticipated deflation rates were because of modulation of wind velocities within the air-flow boundary layer. Bagnold (1941) documented a condition that occurs when dust-laden air causes a reduction in the velocities existing within the air-flow boundary layer near to the ground surface. This occurs as the wind loses momentum to the accelerating soil particles. Thus, as wind speed increases and the concentration of suspended particulate matter increases, the wind speed in the boundary layer is decreased, resulting in the settling of some of the particulate matter. The result of this condition is a modulated stable rate of deflation occurring for all wind speeds over a certain value. It is possible that this condition occurred over the soil-only surfaces at some wind speed between 20 and 25 m/s. That a similar result was not observed over the admixture surfaces was attributed to the 10 to 20 times lesser concentration of suspended soil particles.

4.5.5 Surface Deflation Rate Measurement Repeatability

Because of the large number of test parameters involved in the current study, and in the interest of performing the test series in a cost effective manner, the use of replicate tests was limited in favor of testing the largest possible range of surface configurations. Replicate tests were performed, however, for several admixture configurations, to provide an indication of test-to-test and year-to-year repeatability of the measured results. Not including the 12 cases of gravel layering that were performed in FY 1989, which were each tested twice, nine admixtures were tested in replicate fashion. Of these, five were repeated 3 to 6 times each and were therefore candidates for

demonstrating the repeatability of the measurements. Of the five replicate series, two were not suitable for comparison because of procedural changes made between the earlier and later tests. Procedural changes were made to increase the number or suitability of data obtained during three tests of the 30% 0.28-cm surface (tests BAR-23, 83, and 87) and the three tests of the 30% 0.67-cm surface (tests BAR-5, 9, and 11). It should be noted that procedural changes made between tests did not alter the magnitude of the erosive stress at any given wind speed.

The three test series for which measurement repeatability could be analyzed included 1) three tests of soil-only surfaces (tests BAR-25, 26, and 27), 2) three tests of the 30% Mix 1 admixture surfaces (tests BAR-30, 34, and 38), and 3) six tests of the 30% crushed-rock admixture surfaces (tests BAR-31, 35, 37, 40, 41, and 42). Two additional soil-only tests, BAR-63 and 73, could not be included in the analysis because of procedural changes. Of the crushed-rock tests, comparison of tests BAR-40, 41, and 42 with the other tests was limited to a few selected data, again because of procedural differences between the tests; the latter three tests were performed primarily to provide data on the influence of wind speed on deflation rates (see Section 4.5.4). Because of uncertainties associated with the influence of soil moisture evaporation at 10 m/s, and because the bulk of the data were obtained at 20 m/s, repeatability was judged primarily based on the 20 m/s data.

Results of the three test series are shown, as the surfaces were aged by exposure to 20 m/s wind speed, in Figure 4.11. Variations between the data for the soil-only case were less than those for the two gravel admixtures, possibly indicating that the configuration of gravel on the surfaces influenced deflation rates. The ratio of the standard deviation to the average of three data at each exposure period shown on the plots was 0.22 ± 0.10 for the soil-only case, 0.47 ± 0.17 for the 30% Mix 1 case, and 0.58 ± 0.24 for the 30% crushed-rock case. Thus, nearly all the measurements were shown to be repeatable within less than the magnitude of the deflation rate measurement, and for the soil-only case, within less than one-third of the magnitude of the measurement. A lesser number of 15 m/s data were analyzed and yielded similar results; the soil-only results were repeatable within 50% of the average result, the 30% Mix 1 results within 31%, and the 30% crushed-rock results within 74%.

Three series of surface configurations were tested in different years; however, two of the series were not suitable to be analyzed for measurement repeatability, again because of procedural changes between the early and later tests. However, the third case, two tests of the 30% 1.6-cm admixture were tested in a nearly similar manner and could be compared. Test BAR-10 was performed in FY 1987, and BAR-22 was performed in FY 1988. Comparison between the two tests was possible at four periods in the aging of the surfaces at 20 m/s; 9, 24, 44, and 90-122 min. The

FIGURE 4.11. Results of Deflation Rate Replication Tests for Three Surface Configurations as the Surfaces were Aged by Exposure to 20 m/s Wind Speed. Uncertainty limits include the standard deviation of (typically) three measurements.

measured deflation rates at these exposure durations, in $\text{g}/(\text{m}^2\text{-s})$, were (BAR-10:BAR-22): 1.4:1-3.5 at 9 min, 0.53:0.53 at 24 min, 0.37:0.35 at 44 min, and 0.30:0.29 $\pm$ 0.04 at 90-122 min. Thus, agreement between the two data sets was within 20% for all measurements. As this value was less than the difference between results from replicate tests performed within the same year (see above), the result, although not comprehensive, indicated that erosive stresses applied from year to year were similar and repeatable.

4.6 SURFACE DEFLATION RESULTS

Surface deflation results were determined from the set of data listed in Appendix A. The influences on deflation rate of the following parameters were investigated and are discussed in this section: 1) gravel particle size, 2) depth of layered gravel, 3) gravel mass concentration in admixture, 4) gravel size distribution, and 5) gravel shape (rounded river gravel versus angular crushed-rock gravel). In addition, deflation rate comparisons with the soil-only case are provided, and change in deflation rate with increasing duration of exposure to steady erosive stress is discussed.

4.6.1 Surface Deflation Rate Versus Gravel Size

Two test series provided information on the influence of gravel diameters on surface deflation rates; tests of admixtures of four single-size gravels having diameters ranging from 0.28 to 3 cm and mixed at 30%, by mass, in McGee Ranch silt-loam soil were performed, as were tests of surfaces formed by placing layers of the same gravels on top of the compacted soil. Tests of layered gravels were performed after observations indicated that admixtures tended to form shallow gravel surface layers after 100 to 500 min of exposure to the 20 m/s wind speed. The layered gravels were prepared, therefore, to more closely reproduce an aged surface condition. The admixture surfaces were weathered pre-test, but the layered gravel surfaces were not weathered before the first measurements. The physical characteristics of layered gravels were described in Section 3.4.1.

The specific tests considered were 23, 9, 11, 10, 22, and 24 (admixture tests); 43, 60, 51, 56, 45, 59, 50, and 53 (1x layered gravels); 49, 54, 44, 61, 48, 55, 46, and 62 (2x layered gravels); and 52, 57, 47, and 48 (4x layered gravels). Tests 83 and 87 (performed in FY 1990) were considered possible replicate tests for the 0.28-cm admixture case, but were rejected because they were performed without pre-test weathering, and comparison with the admixture results was therefore not feasible. Test 9 was rejected as a replicate test for the 0.67-cm admixture case because

no 20 m/s data were obtained. For comparison, results of deflation rate measurements from soil-only surfaces (tests 25, 26, 27, 63, and 73) were considered.

Although no great differences were observed between the two soil-only cases, as shown in Figure 4.12, results of soil-only tests 25, 26, and 27 were compared with the admixture tests, as they were exposed to pre-test weathering, and tests 63 and 73 were compared with the layered gravel tests as they were not exposed to pre-test weathering. That deflation during the two soil-only cases was similar in spite of differences in pre-test weathering was attributed to the lack of a protective gravel cover; in the absence of gravel, the soil-only surfaces formed weathered appearances within several minutes of exposure to 20 m/s wind speed, rather than several hundred minutes as was the case for the admixture surfaces. Because of the relatively great susceptibility to wind erosion, the soil-only surfaces rapidly deflated to expose the rims of the metal trays, and therefore failed the test surface. Data obtained after exposure durations of about 20 min were therefore not representative of measured surface shear stresses for two reasons; 1) the surface level was lowered and thus potentially shielded from the scouring velocities by the higher elevation of the boundary layer surfaces, and 2) for exposure durations greater than about 60 min, portions of the tray bottoms were exposed, further decreasing the average elevation of the test surfaces and limiting the surface area exposed. It was interesting to note that the locations of maximum scouring occurred at the trailing edge of the surfaces. This was caused by deflection of air channelled along the side tray edges (once exposed) on contact with the perpendicular plane of the downwind tray edge. For these reasons, direct comparisons between the soil-only and the gravel test cases could only be made with certainty between exposure durations of 1 and 15 min.

Measured surface deflation rates, as the exposed surfaces were aged in the wind tunnel at a wind speed of 20 m/s, are shown for the admixture tests in Figure 4.13 and the layered gravel tests in Figures 4.14 and 4.15. The single-size gravel admixtures included one test at 0.28 cm, two tests at 0.67 and 1.6 cm, and one test at 3 cm. All 1x, 2x, and 4x layered gravel test results were plotted as the average and range of two replicated tests at each gravel size and layer depth. In general, surface deflation rates decreased as gravel size decreased. This trend was most clearly observed in the results of the layered gravels, but was also evident in the results of the single-size gravel admixture tests, with the exception that the 0.67-cm admixture provided greater surface protection than did the 0.28-cm admixture for the first 100 min of exposure to 20 m/s wind speed. This was attributed to an observed loss of a fraction of the 0.28-cm gravel; the fine gravel was blown off the test surface during the first several minutes of exposure to fast wind speeds, and thus contributed to deflation measurements. Surfaces incorporating 0.28-cm gravel did, however, stabilize and form erosion-resistant wind-hardened surface crusts.

FIGURE 4.12 Surface Deflation Rate Results Versus Exposure Duration (Aging) at 20 m/s for Weathered and Unweathered Soil-Only Test Surfaces

FIGURE 4.13. Surface Deflation Rate Results Versus Exposure Duration (Aging) at 20 m/s for Pre-Weathered Gravel Test Surfaces Having 30% Concentrations of 0.28-, 0.67-, 1.6-, and 3-cm Single-Size Gravel Admixtures

FIGURE 4.14. Surface Deflation Rate Results Versus Exposure Duration (Aging) at 20 m/s for 1x and 2x Layered Gravel Surfaces. Plots include the average and standard deviation of two replicate measurements at each exposure duration.

Measured surface deflation rates varied greatly and were influenced by gravel size and exposure duration; at the 20 m/s wind speed, and excluding the soil-only data, the greatest measured surface deflation rate, 38 g/(m²-s), was about 7300 times greater than the least rate, 0.0052 g/(m²-s). The greatest deflation rate was measured from the 30%, 3-cm admixture test case after 1 min of exposure, and the least rate was measured from the 2x, 0.28-cm layered gravel after 100 min of exposure. Fifteen cases of actual and relative deflation rate measurements at selected exposure

FIGURE 4.15. Surface Deflation Rate Results Versus Exposure Duration (Aging) at 20 m/s for 4x Layered Gravel Surfaces. The plot includes the average and standard deviation of two replicate measurements at each exposure duration.

durations are shown in Table 4.6; additional information, at other exposure durations, may be found in Appendix A. For 11 cases, regardless of duration of exposure to 20 m/s wind speed or surface configuration (admixture or layered gravel), the increase in deflation rate as gravel size increased from 0.28 to 3 cm ranged from ~ 5 to 32 times, and averaged 17 ± 8 times (the four 4x layered gravel cases were not considered as they were not performed using either the 1.6 or 3 cm gravels).

The trend toward better surface protection with decreasing gravel size was clear (see Figures 4.13 and 4.14 and Table 4.6) with the exception of one transitional case in which 0.67-cm gravel clearly provided better surface protection than did 0.28-cm gravel (after 10 min of exposure, the deflation rate from the 0.28-cm admixture surface was still large as the fine gravel was blown off the surface until it stabilized). In 13 of the remaining 14 cases shown in Table 4.6, the average results indicated that 0.28 cm gravel provided better protection than 0.67-cm gravel; however, considering uncertainty limits, only 6 of the 15 cases clearly showed lower deflation rates. These results indicated that although the small-diameter gravels provided better surface protection than the large-diameter gravels, the difference between the two small-diameter gravels, 0.28 and 0.67 cm, was not great over the range of exposure durations tested. However, as exposure duration increased, so did the likelihood that the 0.28-cm case would be superior to the 0.67-cm case. Of the 8 cases at 30 min or greater exposure durations (after the primary wind-hardened crust formation period, and

TABLE 4.6. Actual and Relative Surface Deflation Measurements Influenced by Gravel Size and Exposure Duration at 20 m/s

Gravel		Actual Deflation Rate, g/(m ² -s)			
Diameter	Test	Exposure Duration, min			
cm	ID				
Single-Size Admixtures:		10	100	500-1000	
0.28	23	0.89	0.077 ± 0.003	0.016	
0.67	5, 11	0.30 ± 0.13	0.081 ± 0.018	~0.08(a)	
1.6	10, 22	~2	0.28 ± 0.04	~0.28	
3	24	6.1	0.81 ± 0.09	>~0.3	
Soil-Only	25, 26, 27	~3.5	Surface Failed	Surface Failed	
1x Layered Gravels:		1	7	30	100
0.28	43, 60	1.2 ± 0.1	0.105 ± 0.005	0.034 ± 0.008	0.025 ± 0.012
0.67	51, 56	1.4 ± 0.4	0.19 ± 0.10	0.107 ± 0.013	0.027 ± 0.002
1.6	45, 59	4.4 ± 0.6	0.54 ± 0.5(b)	0.27 ± 0.09	0.105 ± 0.015
3	50, 53	12 ± 1	1.75 ± 0.45	0.64 ± 0.10	0.13 ± 0.08
Soil-Only	63, 73	31 ± 3	5.6 ± 0.8	Surface Failed	Surface Failed
2x Layered Gravels:		1	7	30	100
0.28	49, 54	0.22 ± 0.12	~0.04	0.0155 ± 0.0015	0.0052 ± 0.0005
0.67	44, 61	0.285 ± 0.015	0.038 ± 0.016	0.0265 ± 0.0015	0.0090 ± 0.0004
1.6	48, 55	1.10 ± 0.20	0.162 ± 0.088	0.046 ± 0.022	0.041 ± 0.037(b)
3	46, 62	5.3 ± 1.1	0.99 ± 0.51	0.28 ± 0.05	0.165 ± 0.005
Soil-Only	63, 73	31 ± 3	5.6 ± 0.8	Surface Failed	Surface Failed
4x Layered Gravels:		1	7	30	100
0.28	52, 57	0.18 ± 0.02	0.016 ± 0.003	0.0087 ± 0.0023	0.0064 ± 0.0001
0.67	47, 58	0.23 ± 0.05	0.029 ± 0.014	0.0155 ± 0.0015	0.0096 ± 0.0015
Soil-Only	63, 73	31 ± 3	5.6 ± 0.8	Surface Failed	Surface Failed
Average Relative Deflation Rate (Rate Compared with Each 0.28-cm Case)					
		Exposure Duration, min			
Single-Size Admixtures:		10	100	500-1000	
0.28	23	1.0	0.09 (1.0)(c)	0.02 (1.0)(c)	
0.67	5, 11	0.3	0.09 (1.1)	~0.09 (~5)	
1.6	10, 22	~2	0.3 (3.6)	~0.3 (~18)	
3	24	7	0.9 (11)	>~0.3 (>~19)	
Soil-Only	25, 26, 27	~4	6 (65)(d)	6 (310)(d)	
1x Layered Gravels:		1	7	30	100
0.28	43, 60	1.0	0.09 (1.0)(c)	0.03 (1.0)	0.02 (1.0)
0.67	51, 56	1.2	0.16 (1.8)	0.09 (3)	0.02 (1.1)
1.6	45, 59	3.7	~0.5 (~5)(b)	0.2 (8)	0.09 (4)
3	50, 53	10	1.5 (17)	0.5 (19)	0.1 (5)
Soil-Only	63, 73	26	5 (53)	4 (150)(d)	4 (960)(d)
2x Layered Gravels:		1	7	30	100
0.28	49, 54	1.0	~0.2 (~1.0)	0.07 (1.0)	0.02 (1.0)
0.67	44, 61	1.3	0.2 (~1.0)	0.1 (1.7)	0.04 (1.7)
1.6	48, 55	5	0.7 (~4)	0.2 (3)	~0.2 (~8)(b)
3	46, 62	24	5 (~25)	1.3 (18)	0.8 (32)
Soil-Only	63, 73	140	25 (~140)	23 (320)(d)	23 (960)(d)

TABLE 4.6. (contd)

Gravel Diameter cm	Test ID	Average Relative Deflation Rate (Compared with 0.28-cm Cases)			
		Exposure Duration, min			
4x Layered Gravels:		1	7	30	100
0.28	52, 57	1.0	0.9 (1.0)	0.05 (1.0)	0.04 (1.0)
0.67	47, 58	1.3	0.2 (1.8)	0.09 (1.8)	0.05 (1.5)
Soil-Only	63, 73	170	31 (350)	28 (70) ^(d)	28 (250) ^(d)

- (a) An approximate "~" symbol was used to qualify estimates made in the absence of replicated test data.
- (b) Two replicated test cases indicated uncertainties approximately equal to the magnitude of the result, thus providing the possibility that the average result was significantly affected by undetermined measurement errors.
- (c) n (m): n and m equal the relative deflation rates at the listed conditions. n = the relative deflation of the condition versus the deflation rate at the 0.28 cm condition at the initial listed exposure duration (1 or 10 min), m = the relative deflation of the condition versus the deflation rate at the 0.28 cm condition at the same exposure duration.
- (d) Estimated results based on a speculated steady 5 g/(m²-s) deflation rate from soil-only surfaces for exposure durations greater than 15 min. Data was not obtained because the soil-only test surfaces failed after about 20 min exposure durations (the tray rim edges were exposed).

considering measurement uncertainties), 6 test cases indicated better surface protection by the 0.28-cm gravel. Of all 8 aged cases, measured deflation rates from the 0.67-cm surfaces were 1.1 to 5 times greater (average = 2.1 ± 1.3 times greater) than from the 0.28-cm surfaces. The magnitude of this difference might not continue to increase with increasing exposure duration, however, because as the the depth of the surface gravel layers increased, protection provided by 0.67-cm gravel may approach that provided by 0.28-cm gravel (see Section 4.6.2).

Comparison of the admixture and layered gravel surface deflation rate results with the soil-only surface results indicated that, with one exception, the addition of gravel to the surface, whether as an admixture at 30% or as surface layers, decreased surface deflation rates. The exception to this result was the 3-cm admixture, which had greater deflation rates at 10 min of exposure (Table 4.6). It should be noted, however, that the 3-cm admixture surface appeared to stabilize somewhat between 10 and 500 min of exposure, whereas the soil-only surface continued to erode at a greater rate until the surface failed (until the tray rim was exposed). That the 3-cm gravel, the worst case for all tested gravels, provided some degree of surface protection after fully developing an eroded wind-hardened surface was shown in the layered gravel results. A comparison of the soil-only and the 3-cm layered gravel results at exposure durations of 1, 3, 7, and 15 min (the soil-only surfaces failed after about 20 min of exposure) indicated that the 1x gravel layers provided 2.9 ± 0.7 times better surface protection from wind erosion, and the 2x gravel layers provided 7.3 ± 2.6 times better protection.

For the most effective gravel size, 0.28 cm, comparison with the soil-only case provided even greater differences. Over approximately similar exposure durations, although the soil-only surfaces deflated at rates of only about 4 times greater compared with the 0.28 cm admixtures, the 1x layered gravels provided 54 ± 21 times better surface protection than did the soil-only surface, the 2x layers 170 ± 80 times better protection, and the 4x layers 300 ± 160 times better protection. This difference between the two 0.28-cm gravel surface configurations occurred because the admixture surfaces were tested while still completing the process of forming wind-hardened crusts during the 0- to 15- min exposure durations when comparison with the soil-only case was possible, and were thus deflating at rates much greater than those later after the crusts were formed, whereas the layered gravel surfaces were more typical of the wind-hardened condition at the start of the exposures.

4.6.2 Surface Deflation Rate Versus Depth of Layered Gravels

In addition to providing information on the influence of gravel size on deflation rate, the layered gravel tests provided data relating depth of layer to deflation rate for each of the four tested gravel sizes. Results of these measurements are shown in Figures 4.16 and 4.17. Tests included in this analysis were 43-62, inclusive, and 63 and 73. The influence of gravel size on deflation rate, observed by comparing the four plots in the figures, was discussed in the previous section. All measurements indicated that the presence of even a 1x layer provided a measurable improvement in surface resistance to wind erosion, and increasing the thickness of the layered gravel decreased deflation rate. Four data sets for exposure durations between 1 and 15 min indicated that the presence of a 1x gravel layer resulted in 54 ± 21 (0.28 cm), 32 ± 9 (0.67 cm), 9 ± 2 (1.6 cm), and 3.0 ± 0.7 (3 cm) times lower surface deflation rates than those from the soil-only test cases.

Increasing the thickness of layered gravel over the soil surface decreased deflation rates. Results were determined from consideration of data from all seven exposure durations (1 to 100 min), and for two replicate tests performed of each case. For 0.28-cm gravel, the 2x case provided 3.5 ± 1.4 times greater surface protection than did the 1x case, and the 4x case provided 4.7 ± 1.9 times greater protection. Each successive addition of gravel to the test surfaces provided a lesser decrease in deflation rate; the decrease in deflation rate was 54 times between soil-only and 1x, 3.5 times between 1x and 2x, and just 1.3 times between 2x and 4x. Results of tests of the 0.67-cm gravel were similar; the 2x case provided 4.2 ± 0.8 times greater surface protection than did the 1x case, and the 4x case provided 4.8 ± 1.9 times greater protection. Again, each successive addition of gravel to the test surface was less effective than the previous one; the decrease in deflation rate was 32 times between soil-only and 1x, 4.2 times between 1x and 2x, and just 1.1 times between 2x and 4x layered gravels.

FIGURE 4.16 Influence of Layered Gravel Depth on Surface Deflation Rates for 0.28- and 0.67-cm Gravels. Results of two soil-only cases (gravel thickness = 0x) are plotted for comparison.

The two larger gravel sizes were tested at the 1x and 2x thicknesses, but not at the 4x thickness. For the 1.6-cm gravel, the decrease in deflation rate between the 1x and 2x cases was 4.1 ± 1.0 ; for the 3-cm case it was 2.0 ± 0.9 . The lesser change for the 3-cm gravel may have been because of increased deflection of wind gusts toward the surface by the taller position of the rocks, or the larger dimensions of exposed surface areas between the rocks; however, no quantitative data supporting these possible explanations were obtained.

FIGURE 4.17 Influence of Layered Gravel Depth on Surface Deflation Rates for 1.6- and 3-cm Gravels. Results of two soil-only cases (gravel thickness = 0x) are plotted for comparison.

4.6.3 Surface Deflation Rate Versus Gravel Concentration

Three concentrations of gravel, 10, 30, and 50% by mass, were tested as admixtures in McGee Ranch silt-loam soil. Information was obtained during two separate test series, 0.67-cm single-size gravel, and 0.57-cm Mix 1 gravel. Other than the slight difference between the mean gravel sizes, the only significant difference between the two gravels was the distribution of rock diameters within each type of gravel. The 0.67-cm single-size gravel contained rocks with diameters

between 0.48 and 0.95 cm. The 0.57-cm Mix 1 contained a wider distribution of rocks with diameters between 0.2 and 2 cm. All tests were of surfaces that were weathered before testing began. Tests considered included 20 and 21 (10% 0.67 cm); 5 and 11 (30% 0.67 cm); 12 and 13 (50% 0.67 cm); 36 (10% Mix 1); 30, 34, and 38 (30% Mix 1); and 33 (50% Mix 1). Results of tests 25, 26, and 27 (the 0% gravel, soil-only case) were also considered. Tests 9, 63, and 73 were not considered for reasons specified in Section 4.6.1. Comparisons were made primarily of the 20 m/s exposures because of the greater number of data and because of the near independence of deflation to soil moisture at that wind speed. All data were corrected for wind speed variations from target values.

Deflation rate measurements made as the weathered surfaces aged by exposure to 20 m/s wind speed are shown in Figure 4.18. The 0% admixture concentration (the soil-only case) results were repeated in both plots for comparison with results of the gravel admixture cases. Replicate tests were performed of the soil-only, 10% 0.67 cm, 50% 0.67 cm, and 30% Mix 1 admixtures. In these cases, data are plotted as the average of two or three measurements, and the uncertainty limits include the range or standard deviation of the data, respectively. Data from two tests were plotted separately for the 30% 0.67-cm admixture case because the exposure durations for which measurements were obtained were not similar.

Nearly all data indicated that the addition of gravel at any concentration provide improved resistance to wind erosion when compared with the soil-only case. Although the average results of all tests also indicated an increasing level of surface protection as the concentration of gravel increased, only one of the two cases, the 0.67-cm single-size admixture case, showed a significant difference between the 10% and both the 30 and 50% admixture concentrations. The difference in surface protection between the 10, 30, and 50% concentrations gradually decreased as exposure duration approached 1000 min, possibly because the surfaces began to resemble layered gravel surfaces (the 10% surfaces having deflated to a greater extent to form comparable layered gravel surfaces).

Differences between gravel concentrations were most clear for the 0.67-cm single-size admixture case. The addition of 10% gravel provided deflation rates that were about 2 times less than for the 0% (soil-only) condition. The 30 and 50% gravel concentrations provided approximately similar resistance to wind erosion; however, the average deflation rates for the 50% condition were slightly less than those for the 30% condition. Together, deflation rates measured for the greater gravel concentrations were about 8 times less at 10 min, and 3 times less at 100 min exposure duration than were the rates for the 10% condition.

FIGURE 4.18. Surface Deflation Rate Results Versus Exposure Duration (Aging) at 20 m/s as Influenced by Gravel Concentration for two Admixture Cases: 0.67-cm Single-Size Gravel Admixtures, and 0.57-cm Mix1 Admixtures

Although the average of deflation rate measurements for the 0.57-cm Mix 1 admixture case indicated improved resistance to wind erosion as gravel concentration increased, the results were too similar to provide a definite result. That the 10% admixture deflated initially at a lesser rate, and later at a greater rate than expected, may have been because of an unknown interaction of the large gravel size distribution or to undefined measurement errors. In the absence of replicate tests, no conclusion was possible.

4.6.4 Surface Deflation Rate Versus Gravel Size Distribution

Surface admixtures having three differing breadths of gravel size distribution, but similar average gravel sizes, were tested to provide information on the influence of breadth of gravel size distribution on deflation rate. One single-size gravel was compared to two well-graded gravels. The size of the single-size gravel was 0.67 cm (range: 0.48 - 0.95 cm, GSD $\sim$ 1.2); the size of the well-graded gravel Mix 1 was 0.57 cm (range: 0.2 to 2 cm, GSD = 1.82); and the size of Mix 2 was 0.45 cm (range 0.2 to 1 cm, GSD = 1.46). The differences in mean gravel size between the three cases were not expected to cause great differences in deflation rates as differences over a greater size range, between 0.67 and 0.28 cm single-size gravels, were less than 3 times (see Section 4.6.1). Thus, any significant difference in rates of deflation between the three cases might be attributed to the interaction of different sizes of gravel to provided increased or decreased surface protection.

At the 30% admixture condition, the single-size gravel consistently provided better surface protection than did either of the well-graded mixtures; however, the difference was not great. Deflation rates measured at seven intervals between 5 and $\sim$ 320 min of exposure to the 20 m/s wind speed were 2.3 ± 0.5 times greater for Mix 1 and 2.3 ± 0.9 times greater for Mix 2. Although it is possible that the single-size gravel provided relatively better surface protection, the magnitude of the difference was not greater than experimental uncertainty. More important than test averages were trends as the surfaces aged under exposure to wind and formed wind-hardened crusts. For exposure durations greater than 120 min, measured deflation rates from the Mix 1 surfaces continued to be high, averaging about 2.4 times those measured from the single-size gravel admixture surface, but the deflation rates measured from the Mix 2 surfaces decreased to rates that were nearly equal to those from the single-size surface (less than 1.5 times greater). This result may support the conclusion discussed in Section 4.6.2, that the larger gravel sizes continued to provide worse surface protection, even in the extreme case of gravel layers over the soil surface. Although the range of gravel sizes was not greatly different between the 0.67-cm single-size case and Mix 2, Mix 1 was outstanding because it was the only one of the three compared cases having gravel sizes greater than 1 cm.

Well-graded gravels were compared with single-size gravel also at admixture concentrations of 10 and 50% (Figure 4.18), although replicate cases were only performed for the single-size gravel, and Mix 2 was not tested. Results of the comparison at 10% indicated superior surface protection by the single-size gravel; however, data were possibly affected by undetermined measurement errors. Results of the comparison at 50% indicated identical surface protection was provided by both the single-size gravel and the well-graded Mix 1 admixtures.

4.6.5 Surface Deflation Rate Versus Gravel Particle Shape

Particle shape was the final gravel characteristic tested for influence on surface deflation. Rounded river gravel admixtures were compared with angular, crushed-rock admixtures by exposure to 20 m/s wind speed. All tests were of 30%, by mass, gravel admixtures, and using 0.67 cm river gravel and 0.64-cm crushed gravel. Two river gravel tests, 5 and 11, were compared with three crushed gravel tests, 31, 35, and 37. Other candidate crushed gravel tests were not considered because of differences in exposure to wind speeds greater than 15 m/s. Results of this comparison are shown in Figure 4.19. Deflation rates measured from surfaces protected by both types of gravels were nearly identical. Deflation rates measured at seven intervals between 5 and 320 min indicated that the ratio of crushed gravel to river gravel deflation rates was 1.1 ± 0.3 , and thus, the surfaces provided indistinguishably equal surface protection. Data obtained provide results for gravels ranging in size between 0.48 and 0.95 cm. Although it may be likely that smaller gravel sizes would provide a similar result, it is possible that surfaces protected by single layers (1x) of gravels having sizes greater than 1 cm would be influenced by gravel shape. If large-diameter crushed gravels were to form low-profile wind-hardened surface crusts, they could conceivably provide superior resistance to wind erosion compared with river gravel which, lacking extensive flat surfaces, would be likely to form a surface with greater depth of surface relief. Greater surface relief, combined with a less preferential stable orientation for individual river (rounded) rocks, might result in greater wind stress at the soil surface and continued excavation and gravel displacement, and thus provide a surface less resistant to wind erosion.

FIGURE 4.19. Surface Deflation Rate Results at 20 m/s Versus Gravel Particle Shape for 30%, by Mass, 0.67-cm (River Gravel) and 0.64-cm (Crushed Gravel) Admixtures

5.0 CONCLUSIONS AND RECOMMENDATIONS

Test procedures were developed and improved to provide information on the relative susceptibility of soil and gravel surfaces to deflate when exposed to wind erosion stresses within a wind tunnel. Compared with earlier tests (Ligotke 1988), measurements of changing bulk surface mass and soil moisture content (SMC) were emphasized, and measurements of erosion using aerosol and fluoroscopic methods, although useful at times, were de-emphasized. In addition, gravel layers placed over compacted soil-only surfaces provided a method of testing surfaces more representative of those anticipated to exist in the field under drought conditions. The layered gravels provided surface morphologies comparable to those formed by the admixture surfaces after about 500 min of exposure to 20 m/s wind speeds. The range of wind stresses applied to the test surfaces was shown to be representative of field conditions, and measurements supported this result.

Test repeatability and the influences of SMC and wind speed variations on measured surface deflation rates were determined. Evaporation of soil moisture was shown to significantly affect measurements of surface mass made at wind speeds ≤ 10 m/s, but not to affect most measurements made at wind speeds ≥ 15 m/s. Using two methods, the fraction of surface mass loss attributed to dry soil particulate mass was estimated to be $10 \pm 15\%$ and $27 \pm 12\%$. In contrast, the dry particulate mass fraction for tests performed at the greater wind speeds was $97.7 \pm 0.8\%$. This difference was initially attributed to the 10 m/s tests being performed before the greater wind speed tests, at a time when the surfaces were typically drying; however, because moisture evaporation increased linearly with increasing wind speed, and particle erosion rates increased as a power function of wind speed, it was likely that the contribution of soil moisture to surface mass change would be greater at slow wind speeds than at greater wind speeds even under similar SMC conditions. Minor changes in wind speed from test to test, a second potential source of measurement uncertainty, were also considered in the data analyses. For both soil-only and admixture surfaces, the influence of wind speed on erosion rates was determined and used to correct data presented in Appendix A. A third source of measurement uncertainty, experimental variability, was documented for tests performed in the same years and for tests performed in different years. For the three comparable test conditions, the ratios of the standard deviation to the average measured deflation rates were 0.22 ± 0.10 , (soil-only), 0.47 ± 0.17 (30% Mix 1), and 0.58 ± 0.24 (30% crushed-rock), indicating that replicate measurements were achieved within less than the magnitude of the measured deflation rates.

Test parameters were ranked, in order of importance, with respect to wind erosion: 1) gravel particle size, 2) depth of layered gravel, 3) gravel mass concentration in admixture, and 4) gravel size

distribution and shape. The parameters are described below. Included in the first three parameters were comparisons of the soil-only, or baseline, case with cases including gravel; in nearly all cases, the addition of gravel of any size was effective in reducing surface deflation rates.

1. Tests of both gravel admixtures and layered gravels indicated that the smaller gravel sizes provided the best surface protection. For 11 test cases, the measured deflation rate increased 17 ± 8 times as gravel size increased from 0.28 to 3 cm. For example, the addition of 1x layered gravels to compacted soil provided deflation rate reductions compared with the soil-only case of 54 ± 21 times (0.28 cm), 32 ± 9 times (0.67 cm), 9 ± 2 times (1.6 cm), and 3.0 ± 0.7 times (3 cm). Average test results for all cases indicated that the 0.28-cm gravel provided about 1.7 ± 1.1 times better surface protection than the second best size, 0.67 cm, in 13 of 15 cases; however, considering measurement uncertainty, only 6 test cases showed the 0.28-cm gravel to be superior to the 0.67-cm gravel.
2. Increasing the thickness of layered gravels placed on the surface of soil decreased deflation rates; however, the magnitude of the added benefit decreased with each successive layer. For the 0.28-cm gravel case, the addition of a 1x layer provided a reduction in deflation rate of about 54 times compared with the soil-only case. The addition of a 2x layer provided an additional reduction of 3.5 times, and the addition of a 4x layer provided an additional reduction of 1.3 times. For the 0.67-cm gravel case, the addition of gravel layers provided similarly reduced deflation rates of 32, 4.2, and 1.1 times, respectively.
3. Although average results of all tests indicated an increasing level of surface protection as admixture gravel concentration increased, only one of two test cases, the 0.67-cm admixture case, showed a significant difference between the 10% and the 30 and 50% admixture concentrations. Deflation rates from the 10% admixture surfaces were 8 times greater after 10-min exposure to 20 m/s, but decreased to about 3 times greater after 100 min of exposure. The difference continued to decrease as the surfaces were aged and the morphology of the 10% admixture surface approached that of the 30 and 50% admixture surfaces. Comparable surfaces were formed after gravel layers estimated to be similar to the 1x or 2x test cases formed on the surfaces.
4. The influence on deflation rates of both well-graded gravels and gravel shape were of secondary importance. Measured influences were approximately equal to or less than the estimated measurement uncertainty (1.5 to 2 times the magnitude of a given result), compared with single-size river gravels. Single-size gravels provided 2.3 ± 0.5 (Mix 1, 0.2 to 2 cm), and 2.3 ± 0.9 (Mix 2, 0.2 to 1 cm) times better surface protection than did widely distributed (well-graded) gravels. However, after 20 m/s exposures exceeded 120 min, results of surfaces incorporating Mix 2 approached those of the single-size case. That surface protection provided by surfaces prepared using Mix 1 did not approach that provided by the single-size case was speculated to have been caused by the destabilizing presence of gravel in the size range between 1 and 2 cm. Finally, the ratio of deflation rates measured from surfaces containing admixtures of crushed-rock gravels to those containing river gravels was 1.1 ± 0.3 , indicating a very slight preference toward river gravels; however, the difference between the two cases was much less than the estimated measurement uncertainty.

Proper selection of gravel characteristics and placement configuration can provide natural-material protective barrier surfaces resistant to wind erosion over both short and long durations. Layered gravel placed on top of soil can greatly reduce the potential for wind erosion in the critical early period when vegetation is establishing on the surface. Gravel admixtures incorporated within

the surface layer can provide continued protection during future deflationary periods caused by combinations of drought, high temperatures, and wind. The placement of gravel as only admixture or surface layers may leave the surface exposed to potential failure from eolian effects. The use of only layered surface gravel would concentrate surface protection in a narrow band that would be susceptible to displacement by burrowing animals or humans. In the absence of an admixture, failure of the surface armor at places may result in the formation of blowouts or other landforms that could direct surface water runoff and reduce the effectiveness of the barrier. Likewise, placement of only an admixture may contribute to reduced barrier performance. Until vegetation is established before dry windy periods, an unarmored surface would be susceptible to wind erosion. Should deflation occur, the sand fraction of the soil adjacent to the gravel would be concentrated in the surface layer and could contribute to dune formation or enhance deflation by saltation. During wind storms, the saltating sand could also act as an abrasive force and damage seedlings.

Wind tunnel tests indicate that gravel sizes of less than 1 cm provide the best protection from wind erosion. The most appropriate selection would therefore be pea gravel, river or crushed, limited to 0.2 to 0.95 cm [material retained between #10 (Alternate sieve no.) and 3/8-in. sieve sizes]. The use of such a gravel could reduce surface deflation rates during deflationary periods by 54 times compared with soil-only surfaces, and by at least 4 to 17 times compared with larger gravel sizes. Inclusion of sand (< 2 mm) may potentially contribute to decreased surface stability by providing material for transport by saltation, especially for sand sizes of less than 1 mm. The surface admixture should be placed to provide several layers of protection and at sufficient depth to limit the potential impact of burrowing animals and other surface disturbances. For example, if an admixture depth of 30 cm is desired, then assuming an average gravel size of 0.5 cm and 4x equivalent layers, the gravel should be placed at 80 kg per m² of surface, or a mass concentration of about 17%. Surface-layered gravel should be laid at a depth greater than 1x, but less than that which may impede the establishment of vegetation. At an average layer depth of 2x, about 12.5 kg/m² would be required. For the gravel size recommended, it is likely that a gravel layer several diameters deep would not severely impact the establishment of vegetation. At a current delivered pea gravel cost of \$0.009/kg, the combined cost of gravel for admixture and surface layering would be about \$5K/ha (~ \$3K/acre), not including placement costs.

The present study brings to conclusion the first phase of wind erosion tests performed in support of protective barrier development. Second-phase tasks are identified in the project test plan (Ligotke 1989) and include investigations of the impacts of surface crusts, SMC, vegetation (diffuse and deep root structures), and burrowing animals on the susceptibility of protective barrier surfaces to wind erosion. In addition, tests of the influence of microterrain in wind erosion and field

comparison tests are planned. Tests of the influence of fine, medium, and coarse sands mixed into McGee Ranch silt-loam soil have been initiated and have indicated that the destabilizing influence of sand can equal or exceed the stabilizing influence of gravel. Additional tests of the sand and soil combinations should be performed that also incorporate gravel protection. Most tests will include comparison of the design surface with the baseline, soil-only surface. One planned test will include a long-duration exposure of the design surface mixture to wind stress in the presence of saltating sand. The purpose of future tests will be to provide additional information on the response and suitability of the design surface under extreme environmental (eolian) stress.

Other recommended studies include 1) windblown material deposition studies, 2) studies of the potential formation of sand dunes and blowouts, and 3) measurements of wind boundary layer characteristics at full-scale prototype barriers. Deposition studies should include determination of deposition rates of windblown silt and sand as influenced by vegetative and eolian characteristics and conditions. Preliminary work by R.B. Kasper and C.S. Glantz concerning the potential for sand transport at the Hanford Site should also be completed, including a detailed study of potential upwind sources of drifting sand that may impact Hanford protective barriers. Potential adverse impacts of drifting sand include displacement of the fine soil surface layer with coarse-grain sand, increased deflation rates caused by sand particle saltation, displacement of vegetation by sand dune formation, and resultant reduction of drying capacity of the fine soil reservoir. It may be feasible to mitigate the potential impact of off-site sand sources by stabilizing such areas using vegetation or gravel. Finally, measurements of wind boundary layers upwind, at the edges, on top, and between adjacent above-grade protective barriers should be performed, beginning with the prototype barrier planned to be constructed in FY 1991. These studies will provide critical information on the magnitude of surface shear stresses and may reveal both strengths and weaknesses of the present barrier design.

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APPENDIX A

WIND EROSION TEST DATA

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-05											
14	19.94	20	10	58	2.1E-01				20.00	2.1E-01	
15	19.88	60	50	97	1.2E-01				20.00	1.2E-01	
16	19.70	120	140	102	6.1E-02				20.00	6.8E-02	
Test-09											
3	4.90	60	120	9	1.1E-02				5.00	1.1E-02	
4	9.96	30	15	5	1.2E-02				10.00	1.2E-02	
5	9.97	30	45	3	7.2E-03				10.00	7.3E-03	
6	9.96	30	75	4	9.6E-03				10.00	9.8E-03	
7	9.98	30	105	3	7.2E-03				10.00	7.3E-03	
8	10.00	30	135	2	4.8E-03				10.00	4.8E-03	
9	9.98	30	165	3	7.2E-03				10.00	7.3E-03	
10	9.99	60	210	5	6.0E-03				10.00	6.0E-03	
Test-10											
4,5,6,7,8,8	10.05	210	-107	74	2.5E-02				10.00	2.5E-02	
9	10.00	319	-372	43	9.7E-03				10.00	9.7E-03	
10	10.10	533	-798	44	6.0E-03				10.00	5.8E-03	
11	19.60	15	8	250	1.2E+00				20.00	1.4E+00	
12	19.70	15	23	100	4.8E-01				20.00	5.3E-01	
13&14	19.80	30	45	144	3.5E-01				20.00	3.7E-01	
15&16	19.70	30	75	107	2.6E-01				20.00	2.9E-01	
17&18	19.70	30	105	114	2.7E-01				20.00	3.0E-01	
18/19/20	19.60	381	-311	555	1.0E-01				20.00	1.2E-01	
20	19.50	15	508	70	3.4E-01				20.00	4.0E-01	
21	9.94	115	58	15	9.4E-03				10.00	9.6E-03	
Test-11											
4,5,6,7,8	10.00	210	-105	21	7.2E-03				10.00	7.2E-03	
8&9	-10	240	-330	15	4.5E-03						
9	9.90	120	510	4	2.4E-03				10.00	2.5E-03	
9&10	-10	600	870	18	2.2E-03						
10	-10	120	1230	3	1.8E-03						
11,12,13	20.00	9	5	64	5.1E-01				20.00	5.1E-01	
14&15	20.10	10	14	40	2.9E-01				20.00	2.8E-01	
16&17	19.80	30	34	46	1.1E-01				20.00	1.2E-01	
18&19	19.60	45	72	39	6.3E-02				20.00	7.2E-02	
19/20	-20	120	154	97	5.8E-02						
20	19.80	15	222	13	6.3E-02				20.00	6.7E-02	
20/21	-20	180	320	83	3.3E-02						
21	19.60	15	418	14	6.7E-02				20.00	7.7E-02	
22	9.40	120	60	4	2.4E-03				10.00	3.0E-03	
Test-12											
3	10.00	30	45	4	9.6E-03				10.00	9.6E-03	
4	9.90	60	90	8	9.6E-03				10.00	1.0E-02	
5&6	10.00	120	180	13	7.8E-03				10.00	7.8E-03	
6/7&7	10.10	350	415	45	9.3E-03				10.00	9.0E-03	
7&8	10.10	830	1005	39	3.4E-03				10.00	3.3E-03	
8	10.10	120	1480	6	3.6E-03				10.00	3.5E-03	
9	20.40	5	2	68	1.6E+00				20.00	1.4E+00	
10,11,12	20.60	9	8	47	3.8E-01				20.00	3.1E-01	
13&14	20.20	20	22	32	1.2E-01				20.00	1.1E-01	
15&16	19.80	40	52	31	5.6E-02				20.00	6.0E-02	
16/17	19.80	90	117	28	2.2E-02				20.00	2.4E-02	
17	19.40	10	167	5	3.6E-02				20.00	4.4E-02	
17/18	19.30	210	277	47	1.6E-02				20.00	2.1E-02	
18	19.30	10	387	4	2.9E-02				20.00	3.7E-02	
Test-13											
2	10.50	30	15	18	4.3E-02				10.00	3.6E-02	
3,4,5,6	10.20	210	135	35	1.2E-02				10.00	1.1E-02	
6&7	9.90	240	360	26	7.8E-03				10.00	8.1E-03	
7	9.90	120	540	7	4.2E-03				10.00	4.4E-03	
7&8	9.90	720	960	34	3.4E-03				10.00	3.5E-03	
8	10.00	120	1380	5	3.0E-03				10.00	3.0E-03	
9	20.60	3	2	83	2.0E+00				20.00	1.6E+00	
10,11,12	20.60	9	8	88	7.1E-01				20.00	5.7E-01	
13&14	20.30	20	22	55	2.0E-01				20.00	1.8E-01	
15&16	19.80	40	52	42	7.6E-02				20.00	8.1E-02	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-13											
16/17	19.80	120	132	65	3.9E-02				20.00	4.2E-02	
17	19.80	10	197	10	7.2E-02				20.00	7.7E-02	
17/18	19.60	240	322	19	2.7E-02				20.00	3.1E-02	
18	19.50	10	447	3	2.2E-02				20.00	2.6E-02	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-20											
2	9.93	30	15	16	3.9E-02	5	13.5	3.3E-02	10.00	3.9E-02	3.3E-02
3	9.85	30	45	6	1.4E-02	5	3.5	8.4E-03	10.00	1.5E-02	8.9E-03
4	9.74	60	90	12	1.4E-02	5	7.0	8.4E-03	10.00	1.6E-02	9.2E-03
5	9.65	60	150	9	1.1E-02	5	4.0	4.8E-03	10.00	1.2E-02	5.4E-03
5+	9.58	126	243	17	9.8E-03	5	6.5	3.7E-03	10.00	1.1E-02	4.3E-03
6	9.70	120	366	13	7.8E-03	5	3.0	1.8E-03	10.00	8.7E-03	2.0E-03
6+	10.03	423	638	41	7.0E-03	5	5.8	9.8E-04	10.00	6.9E-03	9.7E-04
7	10.09	120	909	10	6.0E-03	5	0.0		10.00	5.8E-03	
8	15.30	7	4	306	3.2E+00	13	304.5	3.1E+00	15.00	2.8E+00	2.8E+00
9	21.25	1	1	515	3.7E+01	13	514.8	3.7E+01	20.00	2.4E+01	2.4E+01
9+	20.68	4	3	582	1.1E+01	13	581.1	1.1E+01	20.00	8.3E+00	8.3E+00
10	20.03	2	6	60	2.2E+00	13	59.6	2.2E+00	20.00	2.1E+00	2.1E+00
10+	20.00	12	13	198	1.2E+00	13	195.4	1.2E+00	20.00	1.2E+00	1.2E+00
11	20.00	2	20	25	9.0E-01	13	24.6	8.9E-01	20.00	9.0E-01	8.9E-01
11+	19.68	38	40	301	5.7E-01	13	292.8	5.6E-01	20.00	6.4E-01	6.2E-01
12	19.97	2	60	11	4.0E-01	13	10.6	3.8E-01	20.00	4.0E-01	3.9E-01
12+	20.00	63	93	218	2.5E-01	13	204.4	2.3E-01	20.00	2.5E-01	2.3E-01
13	20.00	2	125	5	1.8E-01	13	4.6	1.7E-01	20.00	1.8E-01	1.7E-01
14	24.10	1	1	67	4.8E+00	13	66.8	4.8E+00	25.00	6.6E+00	6.6E+00
15	24.10	1	2	68	4.9E+00	13	67.8	4.9E+00	25.00	6.7E+00	6.7E+00
Test-21											
2	10.40	30.0	15	10	2.4E-02	5	7.5	1.8E-02	10.00	2.1E-02	1.6E-02
3	10.34	60.0	45	9	1.1E-02	5	4.0	4.8E-03	10.00	9.6E-03	4.3E-03
4	10.28	60.0	90	16	1.9E-02	5	11.0	1.3E-02	10.00	1.7E-02	1.2E-02
5	10.27	60.0	150	9	1.1E-02	5	4.0	4.8E-03	10.00	9.9E-03	4.4E-03
5+	10.23	120.0	240	17	1.0E-02	5	7.0	4.2E-03	10.00	9.5E-03	3.9E-03
6	10.22	124.0	362	19	1.1E-02	5	8.7	5.1E-03	10.00	1.0E-02	4.7E-03
6+	10.17	165.0	506.5	15	6.6E-03	5	1.3	5.5E-04	10.00	6.2E-03	5.2E-04
7	10.16	120.0	649	12	7.2E-03	5	2.0	1.2E-03	10.00	6.8E-03	1.1E-03
7+	10.21	399.0	908.5	29	5.3E-03	5	<0		10.00	4.9E-03	
8	10.19	120.0	1168	9	5.4E-03	5	<0		10.00	5.1E-03	
9	15.58	8.0	4	36	3.3E-01	13	34.3	3.1E-01	15.00	2.7E-01	2.5E-01
10	20.40	1.5	0.75	175	8.4E+00	13	174.7	8.4E+00	20.00	7.9E+00	7.3E+00
11	20.39	1.5	2.25	141	6.8E+00	13	140.7	6.8E+00	20.00	5.9E+00	5.9E+00
12	20.28	1.0	3.5	76	5.5E+00	13	75.8	5.5E+00	20.00	5.0E+00	5.0E+00
13	20.37	1.0	4.5	69	5.0E+00	13	68.8	5.0E+00	20.00	4.4E+00	4.4E+00
13+	20.09	14.5	12.25	475	2.4E+00	13	471.9	2.4E+00	20.00	2.3E+00	2.3E+00
14	20.10	1.0	20	22	1.6E+00	13	21.8	1.6E+00	20.00	1.5E+00	1.5E+00
14+	19.91	38.5	39.75	348	6.5E-01	13	339.7	6.4E-01	20.00	6.7E-01	6.6E-01
15	19.69	2.0	60	9	3.3E-01	13	8.6	3.1E-01	20.00	3.6E-01	3.4E-01
16	24.92	1.0	0.5	211	1.5E+01	13	210.8	1.5E+01	25.00	1.6E+01	1.6E+01
17	25.76	1.0	1.5	289	2.1E+01	13	288.8	2.1E+01	25.00	1.6E+01	1.6E+01
Test-22											
2	10.38	30.0	15	9	2.2E-02	5	6.5	1.6E-02	10.00	1.9E-02	1.4E-02
3	10.30	30.0	45	6	1.4E-02	5	3.5	8.4E-03	10.00	1.3E-02	7.6E-03
4	10.25	60.0	90	12	1.4E-02	5	7.0	8.4E-03	10.00	1.3E-02	7.7E-03
5	10.27	60.0	150	8	9.6E-03	5	3.0	3.6E-03	10.00	8.8E-03	3.3E-03
5+	10.20	120.0	240	15	9.0E-03	5	5.0	3.0E-03	10.00	8.4E-03	2.8E-03
6	10.23	90.0	345	6	4.8E-03	5	<0		10.00	4.5E-03	
6+	10.15	170.0	475	12	5.1E-03	5	<0		10.00	4.8E-03	
7	10.15	120.0	620	8	4.8E-03	5	<0		10.00	4.6E-03	
7+	10.13	415.0	887.5	21	3.7E-03	5	<0		10.00	3.5E-03	
8	10.12	120.0	1155	N.D.		5			10.00		
9	15.50	5.0	2.5	74	1.1E+00	13	72.9	1.1E+00	15.00	9.0E-01	8.9E-01
10	-20	1.0	0.5	279	2.0E+01	13	278.8	2.0E+01			
10+	21.24	8.5	5.25	634	5.4E+00	13	632.2	5.4E+00	20.00	3.5E+00	3.5E+00
11	-20	1.0	10	45	3.3E+00	13	44.8	3.2E+00			
11+	19.96	14.0	17	143	7.4E-01	13	140.0	7.2E-01	20.00	7.5E-01	7.3E-01
12	20.23	1.0	25	8	5.8E-01	13	7.8	5.6E-01	20.00	5.3E-01	5.2E-01
12+	-20	34.0	42.5	182	3.9E-01	13	174.6	3.7E-01			
13	20.33	1.0	60	5	3.6E-01	13	4.8	3.5E-01	20.00	3.2E-01	3.1E-01
13+	19.91	59.0	90	185	2.3E-01	13	172.2	2.1E-01	20.00	2.3E-01	2.2E-01
14	20.17	1.0	120	4	2.9E-01	13	3.8	2.7E-01	20.00	2.7E-01	2.6E-01
15	20.19	1.0	121	5	3.6E-01	13	4.8	3.5E-01	20.00	3.4E-01	3.2E-01
16	20.52	1.0	122	6	4.3E-01	13	5.8	4.2E-01	20.00	3.6E-01	3.5E-01

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-22											
17	20.25	1	123	4	2.9E-01	13	3.8	2.7E-01	20.00	2.7E-01	2.5E-01
17+	25.16	10	5	602	4.6E+00	13	599.9	4.6E+00	25.00	4.3E+00	4.3E+00
18	25.25	1	10	59	4.3E+00	13	58.8	4.2E+00	25.00	3.9E+00	3.9E+00
18+	25.05	14	18	391	2.0E+00	13	388.0	2.0E+00	25.00	2.0E+00	2.0E+00
19	28.38	1	25	26	1.9E+00	13	25.8	1.9E+00	25.00	5.8E-01	5.8E-01
Test-23											
2	10.42	30.0	15	9	2.2E-02	5	6.5	1.6E-02	10.00	1.9E-02	1.4E-02
3	10.26	30.0	45	5	1.2E-02	5	2.5	6.0E-03	10.00	1.1E-02	5.5E-03
4	10.24	60.0	90	11	1.3E-02	5	6.0	7.2E-03	10.00	1.2E-02	6.7E-03
5	10.21	60.0	150	8	9.6E-03	5	3.0	3.6E-03	10.00	9.0E-03	3.4E-03
6	10.10	120.0	240	15	7.8E-03	5	3.0	1.8E-03	10.00	7.6E-03	1.7E-03
7	10.17	90.0	345	14	1.1E-02	5	6.5	5.2E-03	10.00	1.1E-02	4.9E-03
7+	10.15	180.0	440	12	4.8E-03	5	<0		10.00	4.6E-03	
8	10.17	90.0	615	7	5.6E-03	5	<0		10.00	5.3E-03	
8+	10.12	559.0	939.5	34	4.4E-03	5	<0		10.00	4.2E-03	
9	10.19	120.0	1279	6	3.6E-03	5	<0		10.00	3.4E-03	
10	15.65	2.0	1	49	1.8E+00	13	48.6	1.8E+00	15.00	1.4E+00	1.4E+00
11	~20	1.0	0.5	432	3.1E+01	13	431.8	3.1E+01			
11+	~20	8.5	5.25	350	3.0E+00	13	348.2	3.0E+00			
12	20.04	2.0	10.5	25	9.0E-01	13	24.6	8.9E-01	20.00	8.9E-01	8.8E-01
12+	~20	12.5	17.75	65	3.8E-01	13	62.3	3.6E-01			
13	19.90	2.0	25	9	3.3E-01	13	8.6	3.1E-01	20.00	3.4E-01	3.2E-01
13+	~20	33.0	42.5	61	1.3E-01	13	53.9	1.2E-01			
14	~20	2.0	60	4	1.4E-01	13	3.6	1.3E-01			
14+	19.85	57.0	89.5	59	7.5E-02	13	46.7	5.9E-02	20.00	7.9E-02	6.2E-02
15	19.77	4.0	120	4	7.2E-02	13	3.1	5.7E-02	20.00	7.8E-02	6.1E-02
16	19.73	2.0	123	2	7.2E-02	13	1.6	5.7E-02	20.00	7.9E-02	6.2E-02
17	20.12	2.0	125	2	7.2E-02	13	1.6	5.7E-02	20.00	6.9E-02	5.4E-02
18	20.08	2.0	127	2	7.2E-02	13	1.6	5.7E-02	20.00	7.0E-02	5.5E-02
18+	20	99.0	177.5	52	3.8E-02	13	30.6	2.2E-02	20.00	3.8E-02	2.2E-02
19	20.09	10.0	232	4	2.9E-02	13	1.8	1.3E-02	20.00	2.8E-02	1.3E-02
19+	19.9	182.0	328	43	1.7E-02	13	3.6	1.4E-03	20.00	1.8E-02	1.5E-03
20	19.77	10.0	424	2	1.4E-02	13	<0		20.00	1.6E-02	
20+	24.64	9.5	4.75	359	2.7E+00	13	356.9	2.7E+00	25.00	3.1E+00	3.1E+00
21	24.75	1.0	10	19	1.4E+00	13	18.8	1.4E+00	25.00	1.5E+00	1.5E+00
21+	24.74	14.0	17	160	8.3E-01	13	157.0	8.1E-01	25.00	9.0E-01	8.9E-01
22	24.70	1.0	24.5	11	8.0E-01	13	10.8	7.8E-01	25.00	8.2E-01	8.6E-01
22+	24.57	33.5	41.75	74	1.6E-01	13	66.7	1.4E-01	25.00	1.9E-01	1.7E-01
23	24.39	2.0	59.5	3	1.3E-01	13	2.6	9.3E-02	25.00	1.3E-01	1.1E-01
23+	24.26	58.0	89.5	46	5.7E-02	13	33.4	4.2E-02	25.00	7.4E-02	5.4E-02
24	24.39	2.0	119.5	1	3.6E-02	13	0.6	2.0E-02	25.00	4.5E-02	2.9E-02
Test-24											
2	10.52	30	15	16	3.9E-02	5	11.5	3.3E-02	10.00	3.2E-02	2.7E-02
3	10.39	30	45	9	2.2E-02	5	6.5	1.6E-02	10.00	1.9E-02	1.4E-02
4	10.38	60	90	15	1.8E-02	5	10.0	1.2E-02	10.00	1.6E-02	1.1E-02
5	10.37	60	150	12	1.4E-02	5	7.0	8.4E-03	10.00	1.3E-02	7.4E-03
6	10.21	120	240	19	1.1E-02	5	9.0	5.4E-03	10.00	1.1E-02	5.0E-03
7	10.40	120	360	18	1.1E-02	5	8.0	4.8E-03	10.00	9.4E-03	4.2E-03
7+	10.34	180	510	22	8.8E-03	5	7.0	2.8E-03	10.00	7.9E-03	2.5E-03
8	10.33	120	660	13	7.8E-03	5	3.0	1.8E-03	10.00	7.0E-03	1.6E-03
8+	10.34	452	946	36	5.8E-03	5	<0		10.00	5.1E-03	
9	10.38	120	1232	10	6.0E-03	5	0.0		10.00	5.3E-03	
10	~15.5	1	1	100	7.2E+00	13	99.8	7.2E+00			
11	20.08	1	1	541	3.9E+01	13	540.8	3.9E+01	20.00	3.8E+01	3.8E+01
11+	19.98	9	5	1540	1.3E+01	13	1538.2	1.3E+01	20.00	1.3E+01	1.3E+01
12	20.14	1	10	88	6.4E+00	13	87.8	6.3E+00	20.00	6.1E+00	6.0E+00
12+	20.16	13	17	635	3.7E+00	13	632.3	3.7E+00	20.00	3.5E+00	3.5E+00
13	20.20	1	23	41	3.0E+00	13	40.6	2.9E+00	20.00	2.8E+00	2.8E+00
13+	19.92	30	39	664	1.6E+00	13	657.5	1.6E+00	20.00	1.6E+00	1.6E+00
14	20.00	1	54	16	1.2E+00	13	15.8	1.1E+00	20.00	1.2E+00	1.1E+00
14+	20.08	65	87	802	8.9E-01	13	787.9	8.8E-01	20.00	8.7E-01	8.5E-01
15	20.04	1	120	10	7.2E-01	13	9.8	7.1E-01	20.00	7.1E-01	7.0E-01
16	20.07	1	121	11	8.0E-01	13	10.8	7.8E-01	20.00	7.8E-01	7.6E-01
17	20.23	1	122	10	7.2E-01	13	9.8	7.1E-01	20.00	6.7E-01	6.5E-01
18	20.00	1	123	11	8.0E-01	13	10.8	7.8E-01	20.00	8.0E-01	7.8E-01

Test No.	Actual Wind Speed (m/s)	At (min)	t (avg.) (min)	AM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	AM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-24											
18+	20.09	116	182	567	3.5E-01	13	541.9	3.4E-01	20.00	3.4E-01	3.3E-01
19	~20	1	240	3	2.2E-01	13	2.8	2.0E-01			
19+	24.98	10	5	874	6.6E+00	13	871.9	6.6E+00	25.00	6.7E+00	6.7E+00
20	~25	1	10	42	3.0E+00	13	41.8	3.0E+00			
20+	24.91	14	18	377	1.9E+00	13	374.0	1.9E+00	25.00	2.0E+00	2.0E+00
21	25.13	1	25	22	1.6E+00	13	21.8	1.6E+00	25.00	1.5E+00	1.5E+00
21+	24.69	34	43	544	1.2E+00	13	536.6	1.1E+00	25.00	1.3E+00	1.3E+00
22	24.65	1	60	13	9.4E-01	13	12.8	9.2E-01	25.00	1.1E+00	1.0E+00
Test-25											
2	10.30	30	15	12	2.9E-02	8	8.0	1.9E-02	10.00	2.6E-02	1.7E-02
3	10.28	30	45	11	2.7E-02	8	7.0	1.7E-02	10.00	2.4E-02	1.5E-02
4	10.09	60	90	12	1.4E-02	8	4.0	4.8E-03	10.00	1.4E-02	4.6E-03
5	10.12	60	150	9	1.1E-02	8	1.0	1.2E-03	10.00	1.0E-02	1.1E-03
6	9.96	120	240	16	9.6E-03	8	0.0		10.00	9.8E-03	
7	10.06	120	360	14	8.4E-03	8	<0		10.00	8.2E-03	
7+	10.08	180	510	17	6.8E-03	8	<0		10.00	6.6E-03	
8	10.09	120	660	10	6.0E-03	8	<0		10.00	5.8E-03	
8+	10.06	456	948	36	5.7E-03	8	<0		10.00	5.6E-03	
9	10.04	120	1236	10	6.0E-03	8	<0		10.00	5.9E-03	
10	15.38	2	1	87	3.1E+00	27	86.1	3.1E+00	15.00	2.7E+00	2.7E+00
11	19.74	1	1	474	3.4E+01	27	473.6	3.4E+01	20.00	3.8E+01	3.8E+01
11+	19.74	9	5	859	7.3E+00	27	855.2	7.3E+00	20.00	8.1E+00	8.1E+00
12	19.80	1	10	46	3.3E+00	27	45.6	3.3E+00	20.00	3.6E+00	3.6E+00
13	19.94	1	11	44	3.2E+00	27	43.6	3.1E+00	20.00	3.3E+00	3.2E+00
14	19.66	1	12	38	2.7E+00	27	37.6	2.7E+00	20.00	3.2E+00	3.1E+00
15	19.94	1	13	44	3.2E+00	27	43.6	3.1E+00	20.00	3.3E+00	3.2E+00
15+	19.66	11	19	356	2.3E+00	27	351.1	2.3E+00	20.00	2.7E+00	2.7E+00
16	19.81	1	25	27	2.0E+00	27	26.6	1.9E+00	20.00	2.1E+00	2.1E+00
16+	19.65	34	43	460	9.8E-01	27	444.7	9.5E-01	20.00	1.1E+00	1.1E+00
17	19.58	2	61	20	7.2E-01	27	19.1	6.9E-01	20.00	8.6E-01	8.2E-01
18	19.36	58	91	312	3.9E-01	27	285.9	3.6E-01	20.00	5.1E-01	4.6E-01
19	19.70	2	121	15	5.4E-01	27	14.1	5.1E-01	20.00	6.1E-01	5.8E-01
19+	24.67	5	2	586	9.4E+00	27	584.0	9.4E+00	25.00	1.1E+01	1.1E+01
20	24.73	1	5	110	8.0E+00	27	109.6	7.9E+00	25.00	8.9E+00	8.9E+00
20+	24.35	9	10	548	4.4E+00	27	544.0	4.4E+00	25.00	5.8E+00	5.7E+00
21	24.79	1	15	60	4.3E+00	27	59.6	4.3E+00	25.00	4.7E+00	4.7E+00
21+	24.27	44	38	1174	1.9E+00	27	1154.2	1.9E+00	25.00	2.6E+00	2.6E+00
22	24.24	1	60	25	1.8E+00	27	24.6	1.8E+00	25.00	2.5E+00	2.4E+00
Test-26											
2	10.28	30	15	4	9.6E-03	8	0.0		10.00	8.6E-03	
3	10.26	30	45	7	1.7E-02	8	3.0	7.2E-03	10.00	1.5E-02	6.5E-03
4	10.06	60	90	9	1.1E-02	8	1.0	1.2E-03	10.00	1.1E-02	1.2E-03
5	10.11	60	150	6	7.2E-03	8	<0		10.00	6.9E-03	
6	9.93	120	240	13	7.8E-03	8	<0		10.00	8.1E-03	
7	10.09	120	360	10	6.0E-03	8	<0		10.00	5.8E-03	
7+	10.08	180	510	16	6.4E-03	8	<0		10.00	6.2E-03	
8	10.07	120	660	9	5.4E-03	8	<0		10.00	5.3E-03	
8+	10.04	453	947	30	4.8E-03	8	<0		10.00	4.7E-03	
9	10.04	120	1233	7	4.2E-03	8	<0		10.00	4.1E-03	
10	15.30	2	1	43	1.6E+00	27	42.1	1.5E+00	15.00	1.4E+00	1.3E+00
11	19.76	1	1	418	3.0E+01	27	417.6	3.0E+01	20.00	3.3E+01	3.3E+01
11+	19.57	9	5	628	5.3E+00	27	624.2	5.3E+00	20.00	6.4E+00	6.3E+00
12	19.60	1	10	30	2.2E+00	27	29.6	2.1E+00	20.00	2.6E+00	2.5E+00
13	19.80	1	11	33	2.4E+00	27	32.6	2.4E+00	20.00	2.6E+00	2.6E+00
14	19.85	1	12	28	2.0E+00	27	27.6	2.0E+00	20.00	2.2E+00	2.1E+00
15	20.04	1	13	31	2.2E+00	27	30.6	2.2E+00	20.00	2.2E+00	2.2E+00
15+	19.91	11	19	211	1.4E+00	27	206.1	1.4E+00	20.00	1.4E+00	1.4E+00
16	19.79	1	25	23	1.7E+00	27	22.6	1.6E+00	20.00	1.8E+00	1.8E+00
16+	19.50	34	43	350	7.4E-01	27	334.7	7.1E-01	20.00	9.2E-01	8.8E-01
17	19.32	2	61	13	4.7E-01	27	12.1	4.4E-01	20.00	6.2E-01	5.8E-01
18	>19.2	58	91	327	4.1E-01	27	300.9	3.7E-01			
19	19.69	2	121	16	5.8E-01	27	15.1	5.5E-01	20.00	6.6E-01	6.2E-01
19+	24.65	5	2	889	1.4E+01	27	886.9	1.4E+01	25.00	1.6E+01	1.6E+01
20	24.97	1	5	159	1.1E+01	27	158.6	1.1E+01	25.00	1.2E+01	1.2E+01
20+	24.80	9	10	767	6.2E+00	27	763.0	6.1E+00	25.00	6.7E+00	6.7E+00

Test No.	Actual Wind Speed (m/s)	Δt (min)	ϵ (avg.) (min)	AM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-26											
21	24.80	1	15	97	7.0E+00	27	96.6	7.0E+00	25.00	7.6E+00	7.6E+00
21+	24.39	44	38	1492	2.5E+00	27	1472.2	2.4E+00	25.00	3.2E+00	3.1E+00
22	24.51	1	60	37	2.7E+00	27	36.6	2.6E+00	25.00	3.3E+00	3.2E+00
Test-27											
2	10.27	30	15	21	5.1E-02	8	17.0	4.1E-02	10.00	4.5E-02	3.7E-02
3	10.10	30	45	10	2.4E-02	8	6.0	1.4E-02	10.00	2.3E-02	1.4E-02
4	10.06	60	90	15	1.8E-02	8	7.0	8.4E-03	10.00	1.8E-02	8.2E-03
5	10.07	60	150	12	1.4E-02	8	4.0	4.8E-03	10.00	1.4E-02	4.7E-03
6	9.94	120	240	20	1.2E-02	8	4.0	2.4E-03	10.00	1.2E-02	2.5E-03
7	9.98	120	360	16	9.6E-03	8	0.0		10.00	9.7E-03	
7+	9.94	180	510	19	7.6E-03	8	<0		10.00	7.8E-03	
8	10.00	120	660	11	6.6E-03	8	<0		10.00	6.6E-03	
8+	9.92	480	960	37	5.6E-03	8	<0		10.00	5.8E-03	
9	10.03	120	1260	10	6.0E-03	8	<0		10.00	5.9E-03	
10	>13.2	2	1	94	3.0E+00	27	83.1	3.0E+00			
11	19.74	1	1	449	2.9E+01	27	448.3	2.9E+01	20.00	3.2E+01	3.2E+01
11+	19.76	10	6	638	4.9E+00	27	633.7	4.8E+00	20.00	5.4E+00	5.3E+00
12	19.72	1	11	41	3.0E+00	27	40.6	2.9E+00	20.00	3.3E+00	3.3E+00
13	19.73	1	12	38	2.7E+00	27	37.6	2.7E+00	20.00	3.1E+00	3.0E+00
14	19.73	1	13	51	3.7E+00	27	50.6	3.7E+00	20.00	4.1E+00	4.1E+00
15	19.87	1	14	41	3.0E+00	27	40.6	2.9E+00	20.00	3.1E+00	3.1E+00
15+	19.88	11	20	259	1.7E+00	27	254.1	1.7E+00	20.00	1.8E+00	1.8E+00
16	19.77	1	26	21	1.5E+00	27	20.6	1.5E+00	20.00	1.7E+00	1.6E+00
16+	~20	34	44	350	7.4E-01	27	334.7	7.1E-01			
17	19.45	2	62	12	4.2E-01	27	11.1	4.0E-01	20.00	5.4E-01	5.0E-01
17+	19.53	58	92	262	3.3E-01	27	235.9	2.9E-01	20.00	4.0E-01	3.6E-01
18	19.64	2	122	7	2.5E-01	27	6.1	2.2E-01	20.00	2.9E-01	2.6E-01

Test No.	Actual Wind Speed (m/s)	ΔA (mm)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-30:											
1	5.18	30	15	5	1.2E-02				5.00	1.1E-02	
2	10.38	2	1	14	5.1E-01				10.00	4.4E-01	
3	10.39	4	4	3	5.4E-02				10.00	4.7E-02	
4	10.34	4	8	1	1.8E-02				10.00	1.6E-02	
5	10.32	10	15	3	2.2E-02				10.00	1.9E-02	
6	10.26	20	30	5	1.8E-02				10.00	1.7E-02	
7	10.21	40	60	4	7.2E-03				10.00	6.7E-03	
8	10.06	80	120	7	6.3E-03				10.00	6.2E-03	
9	10.06	160	240	10	4.5E-03				10.00	4.4E-03	
10	-10	320	480	17	3.8E-03						
11	-10	600	940	27	3.3E-03						
12a	15.11	2	1	20	7.2E-01				15.00	7.0E-01	
12b	15.18	2	3	9	3.3E-01				15.00	3.1E-01	
13	20.41	2	1	151	5.5E+00				20.00	4.7E+00	
14	20.35	2	3	65	2.3E+00				20.00	2.1E+00	
15	20.43	2	5	45	1.6E+00				20.00	1.4E+00	
16	20.25	4	8	75	1.4E+00				20.00	1.2E+00	
17	20.45	8	14	183	1.7E+00				20.00	1.4E+00	
18	20.53	2	19	25	9.0E-01				20.00	7.5E-01	
19	20.20	18	29	86	3.5E-01				20.00	3.2E-01	
20	20.15	2	39	10	3.6E-01				20.00	3.4E-01	
21	19.80	37	59	60	1.2E-01				20.00	1.3E-01	
22	19.64	80	117	73	6.6E-02				20.00	7.5E-02	
23	19.79	60	187	183	2.2E-01				20.00	2.4E-01	
24	19.85	170	302	269	1.1E-01				20.00	1.2E-01	
25	9.89	766	383	18	1.7E-03				10.00	1.8E-03	
Test-31											
1	5.06	30	15	8	1.9E-02				5.00	1.9E-02	
2	10.20	2	1	7	2.3E-01				10.00	2.1E-01	
3	10.15	4	4	3	5.4E-02				10.00	5.1E-02	
4	10.16	4	8	2	3.6E-02				10.00	3.4E-02	
5	10.13	10	15	4	2.9E-02				10.00	2.8E-02	
6	10.19	22	31	4	1.3E-02				10.00	1.2E-02	
7	10.01	40	62	7	1.3E-02				10.00	1.3E-02	
8	10.03	80	122	11	9.9E-03				10.00	9.8E-03	
9	9.94	140	232	15	7.7E-03				10.00	7.9E-03	
10	9.87	190	397	20	7.6E-03				10.00	8.0E-03	
11	9.91	682	833	35	3.7E-03				10.00	3.8E-03	
12	14.87	2	1	25	9.0E-01				15.00	9.4E-01	
13	-20	2	1	106	3.8E+00						
14	20.00	2	3	28	1.0E+00				20.00	1.0E+00	
15	19.94	2	5	27	9.8E-01				20.00	1.0E+00	
16	19.77	5	9	26	3.8E-01				20.00	4.1E-01	
17	19.70	7	15	79	8.2E-01				20.00	9.0E-01	
18	20.00	2	18	14	5.1E-01				20.00	5.1E-01	
19	19.93	18	28	44	1.8E-01				20.00	1.8E-01	
20	20.04	2	38	9	3.3E-01				20.00	3.2E-01	
21	19.82	40	59	114	2.1E-01				20.00	2.2E-01	
22	19.78	80	119	101	9.1E-02				20.00	9.8E-02	
23	20.02	160	259	148	6.7E-02				20.00	6.6E-02	
24	19.81	320	479	115	2.6E-02				20.00	2.8E-02	
25	9.86	560	280	17	2.2E-03				10.00	2.3E-03	
Test-32											
1	4.99	30	15	11	2.7E-02				5.00	2.7E-02	
2	-10	2	1	7	2.5E-01						
3	10.18	5	5	3	4.3E-02				10.00	4.1E-02	
4	10.24	3	9	2	4.8E-02				10.00	4.4E-02	
5	10.19	10	15	4	2.9E-02				10.00	2.7E-02	
6	10.07	20	30	4	1.4E-02				10.00	1.4E-02	
7	10.06	40	60	14	2.5E-02				10.00	2.5E-02	
8	9.99	80	120	12	1.1E-02				10.00	1.1E-02	
9	9.93	160	240	14	6.3E-03				10.00	6.5E-03	
10	9.91	322	481	25	5.6E-03				10.00	5.8E-03	
11	9.91	642	963	29	3.3E-03				10.00	3.4E-03	
12	15.03	2	1	26	9.4E-01				15.00	9.3E-01	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	AM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ΔSMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	AM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-32											
13	20.03	2	1	196	7.1E+00				20.00	7.0E+00	
14	20.21	2	3	79	2.9E+00				20.00	2.7E+00	
15	20.08	2	5	49	1.8E+00				20.00	1.7E+00	
16	20.06	4	8	75	1.4E+00				20.00	1.3E+00	
17	20.19	8	14	103	9.3E-01				20.00	8.7E-01	
18	20.19	2	19	22	8.0E-01				20.00	7.4E-01	
19	19.96	18	29	87	3.5E-01				20.00	3.5E-01	
20	19.75	2	39	9	3.3E-01				20.00	2.5E-01	
21	19.69	40	60	87	1.6E-01				20.00	1.7E-01	
22	19.75	80	120	103	9.3E-02				20.00	1.0E-01	
23	20.05	160	240	339	1.5E-01				20.00	1.5E-01	
24	19.70	302	471	142	3.4E-02				20.00	3.8E-02	
25	9.82	700	350	15	1.5E-03				10.00	1.6E-03	
Test-33											
1	5.12	30	15	6	1.4E-02				5.00	1.4E-02	
2	10.25	2	1	5	1.8E-01				10.00	1.7E-01	
3	~10	4	4	0							
4	~10	4	8	0							
5	10.26	10	15	3	2.2E-02				10.00	2.0E-02	
6	10.14	20	30	2	7.2E-03				10.00	6.9E-03	
7	10.08	40	60	4	7.2E-03				10.00	7.0E-03	
8	10.00	80	120	7	6.3E-03				10.00	6.3E-03	
9	9.93	160	240	15	6.8E-03				10.00	6.9E-03	
10	9.66	357	499	23	4.7E-03				10.00	5.2E-03	
11	9.85	600	977	22	2.7E-03				10.00	2.8E-03	
12	14.83	2	1	13	4.7E-01				15.00	5.0E-01	
13	19.80	2	1	87	3.1E+00				20.00	3.4E+00	
14	19.61	2	3	17	6.1E-01				20.00	7.0E-01	
15	20.01	2	5	21	7.6E-01				20.00	7.6E-01	
16	20.02	4	8	26	4.7E-01				20.00	4.7E-01	
17	19.72	8	14	21	1.9E-01				20.00	2.1E-01	
18	19.86	2	19	3	1.1E-01				20.00	1.1E-01	
19	19.76	18	29	20	8.0E-02				20.00	8.7E-02	
20	19.94	2	39	2	7.2E-02				20.00	7.4E-02	
21	19.64	40	60	31	5.6E-02				20.00	6.3E-02	
22	19.65	80	120	56	5.1E-02				20.00	5.7E-02	
23	19.85	160	240	114	5.1E-02				20.00	5.4E-02	
24	19.56	320	480	106	2.4E-02				20.00	2.8E-02	
25	9.79	640	320	9	1.0E-03				10.00	1.1E-03	
Test-34											
1	~5	30	15	7	1.7E-02						
2	10.41	2	1	4	1.4E-01				10.00	1.3E-01	
3	10.23	4	4	1	1.8E-02				10.00	1.7E-02	
4	10.31	4	8	2	3.6E-02				10.00	3.2E-02	
5	10.31	10	15	3	2.2E-02				10.00	1.9E-02	
6	10.25	20	30	2	7.2E-03				10.00	6.6E-03	
7	10.12	40	60	3	5.4E-03				10.00	5.2E-03	
8	10.08	80	120	7	6.3E-03				10.00	6.2E-03	
9	10.03	160	240	16	7.2E-03				10.00	7.2E-03	
10	9.98	320	480	23	5.2E-03				10.00	5.2E-03	
11	9.98	648	964	27	3.0E-03				10.00	3.0E-03	
12	15.24	2	1	11	4.0E-01				15.00	3.7E-01	
13	20.31	2	1	57	2.1E+00				20.00	1.9E+00	
14	20.40	2	3	25	9.0E-01				20.00	7.9E-01	
15	20.36	2	5	22	8.0E-01				20.00	7.0E-01	
16	20.33	4	8	29	5.2E-01				20.00	4.7E-01	
17	20.21	8	14	33	3.0E-01				20.00	2.8E-01	
18	20.25	2	19	8	2.9E-01				20.00	2.7E-01	
19	20.09	18	29	41	1.6E-01				20.00	1.6E-01	
20	20.23	2	39	4	1.4E-01				20.00	1.3E-01	
21	19.85	40	60	44	8.0E-02				20.00	8.4E-02	
22	19.80	80	120	287	2.6E-01				20.00	2.8E-01	
23	20.00	160	240	466	2.1E-01				20.00	2.1E-01	
24	19.85	333	487	267	5.8E-02				20.00	6.1E-02	
25	9.94	602	301	14	1.7E-03				10.00	1.7E-03	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-35											
1	5.08	30	15	11	2.7E-02				5.00	2.6E-02	
2	10.27	2	1	1	3.6E-02				10.00	3.3E-02	
3	10.30	4	4	2	3.6E-02				10.00	3.3E-02	
4	10.27	4	8	1	1.8E-02				10.00	1.6E-02	
5	10.28	10	15	2	1.4E-02				10.00	1.3E-02	
6	10.17	20	30	3	1.1E-02				10.00	1.0E-02	
7	10.12	40	60	5	9.0E-03				10.00	8.7E-03	
8	10.03	80	120	8	7.2E-03				10.00	7.2E-03	
9	10.03	160	240	14	6.3E-03				10.00	6.3E-03	
10	9.93	320	480	17	3.8E-03				10.00	3.9E-03	
11	10.01	640	960	31	3.5E-03				10.00	3.5E-03	
12	15.09	2	1	4	1.4E-01				15.00	1.4E-01	
13	20.07	2	1	19	6.9E-01				20.00	6.7E-01	
14	20.20	2	3	12	4.3E-01				20.00	4.0E-01	
15	20.18	2	5	8	2.9E-01				20.00	2.7E-01	
16	20.06	4	8	10	1.8E-01				20.00	1.8E-01	
17	19.98	8	14	11	9.9E-02				20.00	1.0E-01	
18	20.08	2	19	4	1.4E-01				20.00	1.4E-01	
19	19.90	18	29	17	6.8E-02				20.00	7.1E-02	
20	19.94	2	39	2	7.2E-02				20.00	7.4E-02	
21	19.75	40	60	17	3.1E-02				20.00	3.3E-02	
22	19.73	80	120	30	2.7E-02				20.00	3.0E-02	
23	20.04	160	240	105	4.7E-02				20.00	4.7E-02	
24	19.75	382	511	112	2.1E-02				20.00	2.3E-02	
25	10.00	578	289	13	1.6E-03				10.00	1.6E-03	
Test-36											
1	5.19	30	15	13	3.1E-02				5.00	2.9E-02	
2	10.38	2	1	3	1.1E-01				10.00	9.5E-02	
3	10.37	4	4	2	3.6E-02				10.00	3.2E-02	
4	10.31	4	8	2	3.6E-02				10.00	3.2E-02	
5	10.32	10	15	4	2.9E-02				10.00	2.6E-02	
6	10.23	23	32	5	1.6E-02				10.00	1.5E-02	
7	10.16	37	62	8	1.6E-02				10.00	1.5E-02	
8	10.14	80	120	13	1.2E-02				10.00	1.1E-02	
9	10.06	160	240	23	1.0E-02				10.00	1.0E-02	
10	9.96	320	480	37	8.4E-03				10.00	8.5E-03	
11	10.01	640	960	48	5.4E-03				10.00	5.4E-03	
12	15.20	2	1	15	5.4E-01				15.00	5.1E-01	
13	20.29	2	1	55	2.0E+00				20.00	1.8E+00	
14	20.15	2	3	22	8.0E-01				20.00	7.5E-01	
15	20.29	2	5	18	6.5E-01				20.00	5.9E-01	
16	20.30	4	8	32	5.8E-01				20.00	5.2E-01	
17	20.00	8	14	43	3.9E-01				20.00	3.9E-01	
18	19.98	2	19	8	2.9E-01				20.00	2.9E-01	
19	19.74	18	29	57	2.3E-01				20.00	2.5E-01	
20	19.90	2	39	6	2.2E-01				20.00	2.2E-01	
21	19.75	40	60	87	1.6E-01				20.00	1.7E-01	
22	19.70	80	120	216	2.0E-01				20.00	2.2E-01	
23	19.97	170	205	254	1.1E-01				20.00	1.1E-01	
24	20.07	10	295	102	7.4E-01				20.00	7.2E-01	
25	20.01	10	305	52	3.8E-01				20.00	3.7E-01	
26	19.86	10	315	42	3.0E-01				20.00	3.2E-01	
27	19.85	250	445	700	2.0E-01				20.00	2.1E-01	
28	19.69	10	575	12	8.7E-02				20.00	9.7E-02	
29	19.94	10	585	18	1.3E-01				20.00	1.3E-01	
30	9.93	720	360	19	1.9E-03				10.00	2.0E-03	
Test-37											
1	5.18	30	15	12	2.9E-02				5.00	2.7E-02	
2	10.29	2	1	5	1.8E-01				10.00	1.6E-01	
3	10.31	4	4	2	3.6E-02				10.00	3.2E-02	
4	10.32	4	8	2	3.6E-02				10.00	3.2E-02	
5	10.31	10	15	3	2.2E-02				10.00	1.9E-02	
6	10.19	20	30	5	1.8E-02				10.00	1.7E-02	
7	10.13	40	60	7	1.3E-02				10.00	1.2E-02	
8	10.06	80	120	11	9.9E-03				10.00	9.7E-03	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	AM admix (g)	Total Deflation ($\mu m^2/s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($\mu m^2/s$)	Wind Speed (m/s)	Total Deflation ($\mu m^2/s$)	Dry Mass Deflation ($\mu m^2/s$)
Test-37											
9	10.02	160	240	17	7.7E-03				10.00	7.6E-03	
10	10.18	320	480	27	6.1E-03				10.00	5.7E-03	
11	10.24	640	960	28	3.2E-03				10.00	2.9E-03	
12	15.47	2	1	13	6.5E-01				15.00	5.5E-01	
13	20.58	2	1	77	2.8E+00				20.00	2.3E+00	
14	20.22	2	3	23	8.3E-01				20.00	7.7E-01	
15	20.40	2	5	21	7.6E-01				20.00	6.6E-01	
16	20.33	4	8	18	3.3E-01				20.00	2.9E-01	
17	20.90	8	14	34	3.1E-01				20.00	2.8E-01	
18	20.28	2	19	9	3.3E-01				20.00	3.0E-01	
19	20.17	18	29	64	2.6E-01				20.00	2.4E-01	
20	20.18	2	39	3	1.1E-01				20.00	1.0E-01	
21	20.07	40	60	47	8.5E-02				20.00	8.3E-02	
22	19.76	60	110	50	6.0E-02				20.00	6.5E-02	
23	19.95	10	145	9	6.5E-02				20.00	6.6E-02	
24	19.93	10	155	11	8.0E-02				20.00	8.1E-02	
25	20.04	152	236	169	8.0E-02				20.00	7.9E-02	
26	20.02	10	317	4	2.9E-02				20.00	2.9E-02	
27	19.98	10	327	4	2.9E-02				20.00	2.9E-02	
28	~20	288	476	140	3.5E-02						
29	19.85	10	625	3	2.2E-02				20.00	2.3E-02	
30	19.99	10	635	2	1.4E-02				20.00	1.5E-02	
31	10.03	640	320	15	1.7E-03				10.00	1.7E-03	
Test-38											
1	5.22	30	15	9	2.2E-02				5.00	2.0E-02	
2	10.43	2	1	3	1.1E-01				10.00	9.3E-02	
3	10.48	4	4	1	1.8E-02				10.00	1.5E-02	
4	10.33	4	8	2	3.6E-02				10.00	3.2E-02	
5	10.31	10	15	2	1.4E-02				10.00	1.3E-02	
6	10.29	20	30	3	1.1E-02				10.00	9.8E-03	
7	10.23	40	60	6	1.1E-02				10.00	1.0E-02	
8	10.22	80	120	9	8.1E-03				10.00	7.5E-03	
9	10.18	160	240	17	7.7E-03				10.00	7.2E-03	
10	10.08	320	480	22	5.0E-03				10.00	4.8E-03	
11	10.06	610	945	34	4.0E-03				10.00	3.9E-03	
12	13.20	2	1	15	5.4E-01				15.00	5.1E-01	
13	20.18	2	1	77	2.8E+00				20.00	2.6E+00	
14	20.13	2	3	45	1.6E+00				20.00	1.6E+00	
15	20.13	2	5	41	1.5E+00				20.00	1.4E+00	
16	20.17	4	8	42	7.6E-01				20.00	7.2E-01	
17	19.91	8	14	48	4.3E-01				20.00	4.5E-01	
18	19.81	2	19	9	3.3E-01				20.00	3.5E-01	
19	19.86	18	29	74	3.0E-01				20.00	3.1E-01	
20	19.80	2	39	10	3.6E-01				20.00	3.9E-01	
21	19.72	40	60	97	1.8E-01				20.00	1.9E-01	
22	19.74	60	110	117	1.4E-01				20.00	1.5E-01	
23	19.48	10	145	16	1.3E-01				20.00	1.4E-01	
24	19.66	10	155	20	1.4E-01				20.00	1.6E-01	
25	19.61	140	230	210	1.1E-01				20.00	1.2E-01	
26	19.79	10	305	23	1.7E-01				20.00	1.8E-01	
27	19.86	10	315	22	1.6E-01				20.00	1.7E-01	
28	19.95	300	470	308	7.4E-02				20.00	7.5E-02	
29	20.02	10	625	4	2.9E-02				20.00	2.9E-02	
30	19.86	10	635	5	3.6E-02				20.00	3.8E-02	
31	9.92	728	364	18	1.8E-03				10.00	1.8E-03	
Test-39											
1	3.15	30	15	10	2.4E-02				5.00	2.3E-02	
2	10.36	2	1	6	2.2E-01				10.00	1.9E-01	
3	10.37	4	4	3	5.4E-02				10.00	4.8E-02	
4	~10	4	8	1	1.3E-02						
5	10.29	10	15	4	2.9E-02				10.00	2.6E-02	
6	10.21	20	30	4	1.4E-02				10.00	1.3E-02	
7	10.14	40	60	15	2.7E-02				10.00	2.6E-02	
8	10.09	80	120	12	1.1E-02				10.00	1.1E-02	
9	10.00	160	240	20	9.0E-03				10.00	9.0E-03	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admin (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-39											
10	9.92	320	480	31	7.0E-03				10.00	7.2E-03	
11	10.01	640	960	32	3.6E-03				10.00	3.6E-03	
12	15.06	2	1	26	9.4E-01				15.00	9.2E-01	
13	20.15	2	1	146	5.3E+00				20.00	5.0E+00	
14	19.95	2	3	55	2.0E+00				20.00	2.0E+00	
15	20.19	2	5	46	1.7E+00				20.00	1.6E+00	
16	20.19	4	8	56	1.0E+00				20.00	9.5E-01	
17	20.01	8	14	58	5.2E-01				20.00	5.2E-01	
18	20.10	2	19	18	6.5E-01				20.00	6.3E-01	
19	19.98	18	29	69	2.8E-01				20.00	2.8E-01	
20	19.80	2	39	14	5.1E-01				20.00	5.4E-01	
21	19.81	48	64	108	1.6E-01				20.00	1.7E-01	
22	19.66	52	114	140	1.9E-01				20.00	2.2E-01	
23	19.60	10	145	18	1.3E-01				20.00	1.5E-01	
24	19.94	10	155	26	1.9E-01				20.00	1.9E-01	
25	19.95	140	230	94	4.9E-02				20.00	4.9E-02	
26	20.05	10	305	10	7.2E-02				20.00	7.1E-02	
27	19.90	10	315	8	5.8E-02				20.00	6.0E-02	
28	19.99	300	470	173	4.2E-02				20.00	4.2E-02	
29	19.86	11	626	4	2.6E-02				20.00	2.8E-02	
30	19.82	9	635	4	3.2E-02				20.00	3.4E-02	
31	19.73	710	995	152	1.5E-02				20.00	1.7E-02	
Test-40											
1	20.54	2	1	417	1.5E+01				20.00	1.2E+01	
2	20.41	2	3	99	3.6E+00				20.00	3.1E+00	
3	20.34	6	7	172	2.1E+00				20.00	1.8E+00	
4	20.16	10	15	128	9.3E-01				20.00	8.8E-01	
5	10.23	2	1	1	3.6E-02				10.00	3.3E-02	
6	10.25	2	3	1	3.6E-02				10.00	3.3E-02	
7	10.25	6	7	2	2.4E-02				10.00	2.2E-02	
8	10.19	10	15	2	1.4E-02				10.00	1.4E-02	
9	10.19	20	30	4	1.4E-02				10.00	1.4E-02	
10	10.14	40	60	9	1.6E-02				10.00	1.5E-02	
11	10.12	80	120	9	8.1E-03				10.00	7.8E-03	
12	10.06	160	240	14	6.3E-03				10.00	6.2E-03	
13	10.00	181	410	13	5.2E-03				10.00	5.2E-03	
14	10.05	960	980	37	2.8E-03				10.00	2.7E-03	
15	25.83	2	1	716	2.6E+01				25.00	1.9E+01	
16	10.13	30	15	2	4.8E-03				10.00	4.6E-03	
17	25.39	2	1	164	5.9E+00				25.00	5.2E+00	
18	10.13	30	15	1	2.4E-03				10.00	2.3E-03	
19	25.38	2	1	105	3.8E+00				25.00	3.3E+00	
20	10.21	30	15	2	4.8E-03				10.00	4.5E-03	
21	25.44	2	1	83	3.0E+00				25.00	2.6E+00	
22	15.08	2	1	0					15.00		
23	10.17	30	15	1	2.4E-03				10.00	2.3E-03	
24	15.69	10	5	1	7.2E-03				15.00	7.0E-03	
25	19.90	10	5	6	4.3E-02				20.00	4.5E-02	
26	25.32	10	5	231	1.7E+00				25.00	1.5E+00	
27	10.03	30	15	2	4.8E-03				10.00	4.8E-03	
28	15.02	10	5	0					15.00		
29	19.84	10	5	4	2.9E-02				20.00	3.1E-02	
30	25.18	10	5	129	9.3E-01				25.00	8.8E-01	
Test-41											
1	21.77	2	1	322	1.2E+01				20.00	6.3E+00	
2	21.28	2	3	63	2.3E+00				20.00	1.5E+00	
3	21.03	6	7	103	1.2E+00				20.00	8.7E-01	
4	20.62	10	15	78	5.6E-01				20.00	4.6E-01	
5	10.55	2	1	2	7.2E-02				10.00	6.0E-02	
6	10.59	2	3	1	3.6E-02				10.00	2.9E-02	
7	10.43	6	7	2	2.4E-02				10.00	2.1E-02	
8	10.44	10	15	2	1.4E-02				10.00	1.2E-02	
9	10.31	20	30	4	1.4E-02				10.00	1.3E-02	
10	10.28	40	60	6	1.1E-02				10.00	9.8E-03	
11	10.25	80	120	9	8.1E-03				10.00	7.5E-03	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	AM admix (g)	Total Deflation ($\mu\text{m}^2/\text{s}$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (mm/s)	ΔM soil (g)	Dry Mass Deflation ($\mu\text{g}/\text{m}^2/\text{s}$)	Wind Speed (m/s)	Total Deflation ($\mu\text{g}/\text{m}^2/\text{s}$)	Dry Mass Deflation ($\mu\text{g}/\text{m}^2/\text{s}$)
Test-41:											
12	10.20	160	240	16	7.2E-03				10.00	6.7E-03	
13	10.11	376	508	26	5.0E-03				10.00	4.8E-03	
14	10.11	709	1050	29	3.0E-03				10.00	2.8E-03	
15	20.12	2	1	23	8.3E-01				20.00	8.0E-01	
16	10.26	30	15	1	2.4E-03				10.00	2.2E-03	
17	19.93	2	1	21	7.6E-01				20.00	7.8E-01	
18	10.27	29	15	2	5.0E-03				10.00	4.5E-03	
19	20.04	2	1	25	9.0E-01				20.00	8.9E-01	
20	10.23	30	15	2	4.8E-03				10.00	4.5E-03	
21	15.26	2	1	1	3.6E-02				15.00	3.3E-02	
22	20.11	2	1	20	7.2E-01				20.00	7.0E-01	
23	10.21	30	15	2	4.8E-03				10.00	4.5E-03	
24	15.14	10	5	2	1.4E-02				15.00	1.4E-02	
25	20.08	10	5	83	6.0E-01				20.00	5.8E-01	
26	10.17	30	15	1	2.4E-03				10.00	2.3E-03	
27	15.07	10	5	2	1.4E-02				15.00	1.4E-02	
28	19.88	10	5	255x					20.00		
29	19.95	10	15	77	5.6E-01				20.00	5.7E-01	
30	19.83	10	25	30	2.2E-01				20.00	2.3E-01	
31	10.06	30	15	2	4.8E-03				10.00	4.7E-03	
32	19.81	10	5	23	1.7E-01				20.00	1.8E-01	
Test-42:											
1	21.08	2	1	316	1.1E+01				20.00	7.9E+00	
2	20.86	2	3	53	1.9E+00				20.00	1.4E+00	
3	20.47	6	7	110	1.3E+00				20.00	1.1E+00	
4	20.39	10	15	79	5.7E-01				20.00	5.0E-01	
5	10.36	2	1	1	3.6E-02				10.00	3.2E-02	
6	10.41	2	3	1	3.6E-02				10.00	3.1E-02	
7	10.29	6	7	2	2.4E-03				10.00	2.1E-02	
8	10.26	10	15	3	2.2E-02				10.00	2.0E-02	
9	10.23	20	30	4	1.4E-02				10.00	1.3E-02	
10	10.13	40	60	6	1.1E-02				10.00	1.0E-02	
11	10.12	80	120	10	9.0E-03				10.00	8.7E-03	
12	10.06	160	240	17	7.7E-03				10.00	7.5E-03	
13	10.05	180	410	15	6.0E-03				10.00	5.9E-03	
14	10.07	960	980	49	3.7E-03				10.00	3.6E-03	
15	25.26	2	1	551	2.0E+01				25.00	1.8E+01	
16	10.20	30	15	2	4.8E-03				10.00	4.5E-03	
17	25.13	2	1	169	6.1E+00				25.00	5.8E+00	
18	10.20	30	15	1	2.4E-03				10.00	2.2E-03	
19	25.36	2	1	119	4.3E+00				25.00	3.8E+00	
20	10.19	30	15	2	4.8E-03				10.00	4.5E-03	
21	15.21	2	1	0					15.00		
22	25.36	2	1	91	3.3E+00				25.00	2.9E+00	
23	10.16	30	15	1	2.4E-03				10.00	2.3E-03	
24	15.10	11	6	1	6.6E-03				15.00	6.3E-03	
25	19.70	10	5	6	4.3E-02				20.00	4.8E-02	
26	24.98	10	5	222	1.6E+00				25.00	1.6E+00	
27	10.06	30	15	2	4.8E-03				10.00	4.7E-03	
28	15.04	10	5	1	7.2E-03				15.00	7.1E-03	
29	19.93	10	5	4	2.9E-02				20.00	3.0E-02	
30	25.37	10	5	182	1.3E+00				25.00	1.2E+00	
Test-43											
1	19.72	2	1	31.9	1.2E+00				20.00	1.3E+00	
2	20.28	2	3	5.9	2.1E-01				20.00	1.9E-01	
3	20.17	6	7	8.7	1.0E-01				20.00	9.9E-02	
4	19.84	10	15	4.9	3.5E-02				20.00	3.7E-02	
5	19.87	20	30	7	2.5E-02				20.00	2.6E-02	
6	19.83	40	60	9.8	1.8E-02				20.00	1.8E-02	
7	20.11	40	100	21	3.8E-02				20.00	3.7E-02	
Test-44											
1	20.98	2	1	10.6	3.8E-01				20.00	2.7E-01	
2	20.45	2	3	2	7.2E-02				20.00	6.5E-02	
3	20.22	6	7	2	2.4E-02				20.00	2.2E-02	
4	20.17	10	15	4	2.9E-02				20.00	2.7E-02	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ΔSMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-44											
5	20.10	20	30	8	2.9E-02				20.00	2.8E-02	
6	19.98	40	60	9	1.6E-02				20.00	1.6E-02	
7	19.89	40	100	5	9.0E-03				20.00	9.4E-03	
Test-45											
1	20.06	2	1	144	5.2E+00				20.00	5.1E+00	
2	20.14	2	3	36	1.3E+00				20.00	1.2E+00	
3	19.98	6	7	49	5.9E-01				20.00	5.9E-01	
4	20.03	10	15	49	3.5E-01				20.00	3.5E-01	
5	20.01	20	30	49	1.8E-01				20.00	1.8E-01	
6	19.91	40	60	109	2.0E-01				20.00	2.0E-01	
7	19.93	40	100	64	1.2E-01				20.00	1.2E-01	
Test-46											
1	20.59	2	1	217	7.8E+00				20.00	6.4E+00	
2	20.36	2	3	72	2.6E+00				20.00	2.3E+00	
3	20.20	6	7	135	1.6E+00				20.00	1.5E+00	
4	20.02	10	15	60	4.3E-01				20.00	4.3E-01	
5	19.77	20	30	85	3.1E-01				20.00	3.3E-01	
6	20.18	40	60	186	3.4E-01				20.00	3.2E-01	
7	20.06	40	100	91	1.6E-01				20.00	1.6E-01	
Test-47											
1	19.91	2	1	7.5	2.7E-01				20.00	2.8E-01	
2	20.03	2	3	2.3	8.3E-02				20.00	8.2E-02	
3	20.19	6	7	1.3	1.6E-02				20.00	1.5E-02	
4	20.00	10	15	5.7	4.1E-02				20.00	4.1E-02	
5	19.93	20	30	4.7	1.7E-02				20.00	1.7E-02	
6	19.69	40	60	4.9	8.9E-03				20.00	9.9E-03	
7	19.57	40	100	5.3	9.6E-03				20.00	1.1E-02	
Test-48											
1	20.08	2	1	26	9.4E-01				20.00	9.1E-01	
2	20.18	2	3	5	1.8E-01				20.00	1.7E-01	
3	19.94	6	7	6	7.2E-02				20.00	7.4E-02	
4	20.01	10	15	8	5.8E-02				20.00	5.8E-02	
5	19.82	20	30	6	2.2E-02				20.00	2.3E-02	
6	19.82	40	60	22	4.0E-02				20.00	4.2E-02	
7	19.98	40	100	43	7.8E-02				20.00	7.8E-02	
Test-49											
1	19.62	2	1	8	2.9E-01				20.00	3.3E-01	
2	19.76	2	3	0					20.00		
3	19.72	6	7	3	3.6E-02				20.00	4.0E-02	
4	19.90	10	15	4	2.9E-02				20.00	3.0E-02	
5	20.03	20	30	4	1.4E-02				20.00	1.4E-02	
6	19.84	40	60	4	7.2E-03				20.00	7.6E-03	
7	19.91	40	100	3	5.4E-03				20.00	5.6E-03	
Test-50											
1	19.78	2	1	288.4	1.0E+01				20.00	1.1E+01	
2	20.22	2	3	192	6.9E+00				20.00	6.4E+00	
3	19.91	6	7	180	2.2E+00				20.00	2.2E+00	
4	20.08	10	15	153	1.1E+00				20.00	1.1E+00	
5	20.06	20	30	153	5.5E-01				20.00	5.4E-01	
6	19.83	40	60	163	2.9E-01				20.00	3.1E-01	
7	19.74	40	100	27	4.9E-02				20.00	5.3E-02	
Test-51											
1	19.67	2	1	24	8.7E-01				20.00	9.7E-01	
2	19.96	2	3	4	1.4E-01				20.00	1.5E-01	
3	20.01	6	7	8	9.6E-02				20.00	9.6E-02	
4	20.00	10	15	9	6.5E-02				20.00	6.5E-02	
5	19.90	20	30	25	9.0E-02				20.00	9.4E-02	
6	19.85	40	60	29	5.2E-02				20.00	5.5E-02	
7	19.80	40	100	13	2.3E-02				20.00	2.5E-02	
Test-52											
1	-20	2	1	5.5	2.0E-01						
2	20.03	2	3	1.5	5.4E-02				20.00	5.4E-02	
3	20.18	6	7	1.7	2.0E-02				20.00	1.9E-02	
4	20.12	10	15	1.5	1.1E-02				20.00	1.0E-02	
5	20.03	20	30	1.8	6.5E-03				20.00	6.4E-03	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-52											
6	20.10	40	60	5.5	9.9E-03				20.00	9.6E-03	
7	20.06	40	100	3.7	6.7E-03				20.00	6.5E-03	
Test-53											
1	20.39	2	1	406	1.5E+01				20.00	1.3E+01	
2	20.47	2	3	105	3.8E+00				20.00	3.3E+00	
3	20.33	6	7	124	1.5E+00				20.00	1.3E+00	
4	20.30	10	15	151	1.1E+00				20.00	9.8E-01	
5	20.31	20	30	229	8.3E-01				20.00	7.4E-01	
6	20.17	40	60	129	2.3E-01				20.00	2.2E-01	
7	20.08	40	100	117	2.1E-01				20.00	2.1E-01	
Test-54											
1	20.02	2	1	2.9	1.0E-01				20.00	1.0E-01	
2	20.05	2	3	1.1	4.0E-02				20.00	3.9E-02	
3	20.13	6	7	<0.5					20.00		
4	20.16	10	15	1.6	1.2E-02				20.00	1.1E-02	
5	20.14	20	30	4.8	1.7E-02				20.00	1.7E-02	
6	19.90	40	60	4.8	8.7E-03				20.00	9.0E-03	
7	20.00	40	100	2.6	4.7E-03				20.00	4.7E-03	
Test-55											
1	20.08	2	1	36	1.3E+00				20.00	1.3E+00	
2	20.14	2	3	10	3.6E-01				20.00	3.4E-01	
3	20.07	6	7	21	2.5E-01				20.00	2.5E-01	
4	20.11	10	15	17	1.2E-01				20.00	1.2E-01	
5	20.16	20	30	20	7.2E-02				20.00	6.8E-02	
6	20.09	40	60	23	4.2E-02				20.00	4.0E-02	
7	19.90	40	100	2	3.5E-03				20.00	3.7E-03	
Test-56											
1	20.08	2	1	51.4	1.9E+00				20.00	1.8E+00	
2	20.08	2	3	9	3.3E-01				20.00	3.2E-01	
3	19.98	6	7	24	2.9E-01				20.00	2.9E-01	
4	20.08	10	15	27	2.0E-01				20.00	1.9E-01	
5	19.98	20	30	34	1.2E-01				20.00	1.2E-01	
6	19.75	40	60	28.6	5.2E-02				20.00	5.6E-02	
7	19.99	40	100	16	2.9E-02				20.00	2.9E-02	
Test-57											
1	~20	2	1	4.3	1.6E-01						
2	19.93	2	3	1.7	6.1E-02				20.00	6.3E-02	
3	19.98	6	7	1.1	1.3E-02				20.00	1.3E-02	
4	19.87	10	15	0.8	5.8E-03				20.00	6.0E-03	
5	19.94	20	30	3	1.1E-02				20.00	1.1E-02	
6	19.86	40	60	3.7	6.7E-03				20.00	7.0E-03	
7	19.99	40	100	3.5	6.3E-03				20.00	6.3E-03	
Test-58											
1	20.69	2	1	6.4	2.3E-01				20.00	1.8E-01	
2	20.42	2	3	3.9	1.4E-01				20.00	1.2E-01	
3	20.32	6	7	4	4.8E-02				20.00	4.3E-02	
4	20.20	10	15	5.3	3.8E-02				20.00	3.6E-02	
5	20.12	20	30	3.9	1.4E-02				20.00	1.4E-02	
6	19.74	40	60	5.8	1.0E-02				20.00	1.1E-02	
7	20.07	40	100	4.6	8.3E-03				20.00	8.1E-03	
Test-59											
1	19.89	2	1	101	3.6E+00				20.00	3.4E+00	
2	20.11	2	3	30	1.1E+00				20.00	1.0E+00	
3	20.00	6	7	41	4.9E-01				20.00	4.9E-01	
4	20.04	10	15	57	4.1E-01				20.00	4.1E-01	
5	19.98	20	30	100	3.6E-01				20.00	3.6E-01	
6	19.96	40	60	97	1.8E-01				20.00	1.8E-01	
7	19.86	40	100	47	8.5E-02				20.00	8.9E-02	
Test-60											
1	19.95	2	1	31.1	1.1E+00				20.00	1.1E+00	
2	20.06	2	3	4.8	1.7E-01				20.00	1.7E-01	
3	20.30	6	7	9.7	1.2E-01				20.00	1.1E-01	
4	20.17	10	15	9.8	7.1E-02				20.00	6.7E-02	
5	20.15	20	30	12	4.3E-02				20.00	4.1E-02	
6	20.01	40	60	11	2.0E-02				20.00	2.0E-02	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ΔSMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-60											
7	19.90	40	100	7	1.3E-02				20.00	1.3E-02	
Test-61											
1	20.21	2	1	8.9	3.2E-01				20.00	3.0E-01	
2	20.22	2	3	2.3	8.3E-02				20.00	7.7E-02	
3	20.37	6	7	5	6.0E-02				20.00	5.3E-02	
4	20.49	10	15	4	2.9E-02				20.00	2.4E-02	
5	20.37	20	30	8	2.9E-02				20.00	2.5E-02	
6	20.23	40	60	7.2	1.3E-02				20.00	1.2E-02	
7	20.16	40	100	5.1	9.2E-03				20.00	8.7E-03	
Test-62											
1	20.34	2	1	141	5.1E+00				20.00	4.2E+00	
2	20.27	2	3	28	1.0E+00				20.00	9.2E-01	
3	20.14	6	7	42	5.1E-01				20.00	4.8E-01	
4	20.07	10	15	43	3.1E-01				20.00	3.0E-01	
5	20.00	20	30	63	2.3E-01				20.00	2.3E-01	
6	20.13	40	60	136	2.5E-01				20.00	2.3E-01	
7	20.09	40	100	99	1.8E-01				20.00	1.7E-01	
Test-63											
1	20.75	2	1	1044	3.8E+01				20.00	2.8E+01	
2	20.57	2	3	354	1.3E+01				20.00	1.0E+01	
3	20.29	6	7	441	5.3E+00				20.00	4.7E+00	
4	20.20	10	15	644	4.7E+00				20.00	4.3E+00	
5	20.12	20	30	989	3.6E+00				20.00	3.4E+00	
6	19.70	20	50	603	2.2E+00				20.00	2.5E+00	
Test-64											
1	20.53	2	1	2019	7.3E+01				20.00	5.9E+01	
2	20.48	2	3	744	2.7E+01				20.00	2.2E+01	
3	20.31	6	7	1255	1.5E+01				20.00	1.3E+01	
4	20.20	10	15	1159	8.4E+00				20.00	7.7E+00	
Test-65											
1	20.31	2	1	10670	3.9E+02				20.00	3.4E+02	
2	20.08	2	3	3334	1.2E+02				20.00	1.2E+02	
Test-66											
1	20.60	2	1	1350	4.9E+01				20.00	3.8E+01	
2	20.59	2	3	501	1.8E+01				20.00	1.4E+01	
3	20.35	6	7	726	8.7E+00				20.00	7.6E+00	
4	20.34	10	15	905	6.5E+00				20.00	5.7E+00	
Test-67											
1	20.75	2	1	4524	1.6E+02				20.00	1.2E+02	
2	20.47	2	3	2370	8.6E+01				20.00	7.0E+01	
3	20.11	6	7	3364	4.1E+01				20.00	3.9E+01	
Test-68											
1	20.89	2	1	2080	7.5E+01				20.00	5.2E+01	
2	20.57	2	3	926	3.3E+01				20.00	2.6E+01	
3	20.35	6	7	1520	1.8E+01				20.00	1.6E+01	
4	20.17	10	15	1547	1.1E+01				20.00	1.0E+01	
Test-69											
1	20.55	2	1	9620	3.5E+02				20.00	2.8E+02	
2	20.09	2	3	4045	1.5E+02				20.00	1.4E+02	
3	19.76	6	7	2928	3.5E+01				20.00	3.9E+01	
Test-70											
1	20.37	2	1	1288	4.7E+01				20.00	4.0E+01	
2	20.26	2	3	491	1.8E+01				20.00	1.6E+01	
3	20.14	6	7	783	9.4E+00				20.00	8.9E+00	
4	20.19	10	15	679	4.9E+00				20.00	4.5E+00	
Test-71											
1	19.93	2	1	1580	5.7E+01				20.00	5.9E+01	
2	19.84	2	3	718	2.6E+01				20.00	2.8E+01	
3	20.02	6	7	1278	1.5E+01				20.00	1.5E+01	
4	19.91	10	15	1288	9.3E+00				20.00	9.7E+00	
Test-72											
1	19.99	2	1	3983	1.4E+02				20.00	1.4E+02	
2	19.97	2	3	2278	8.2E+01				20.00	8.3E+01	
3	19.92	6	7	3265	3.9E+01				20.00	4.1E+01	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation ($g/m^2 \cdot s$)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation ($g/m^2 \cdot s$)	Wind Speed (m/s)	Total Deflation ($g/m^2 \cdot s$)	Dry Mass Deflation ($g/m^2 \cdot s$)
Test-72 4	19.91	10	15	1989	1.4E+01				20.00	1.5E+01	
Test-73 1	19.92	2	1	910	3.3E+01				20.00	3.4E+01	
2	20.15	2	3	325	1.2E+01				20.00	1.1E+01	
3	20.11	6	7	560	6.7E+00				20.00	6.4E+00	
4	20.09	10	15	525	3.8E+00				20.00	3.7E+00	
Test-74 1	19.77	2	1	10296	3.7E+02				20.00	4.1E+02	
2	19.67	2	3	3930	1.4E+02				20.00	1.6E+02	
Test-75 1	20.35	2	1	1906	6.9E+01				20.00	6.0E+01	
2	20.17	2	3	945	3.4E+01				20.00	3.2E+01	
3	20.05	6	7	1766	2.1E+01				20.00	2.1E+01	
4	19.88	10	15	1569	1.1E+01				20.00	1.2E+01	
Test-76 1	20.19	2	1	9135	3.3E+02				20.00	3.1E+02	
2	19.96	2	3	3815	1.4E+02				20.00	1.4E+02	
Test-77 2	20.60	2	1	1263	4.6E+01				20.00	3.6E+01	
Test-78 1	20.38	2	1	1201	4.3E+01				20.00	3.7E+01	

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-80											
3	19.00	1	1	205	1.3E+01				20.00	2.0E+01	
4	20.10	2	2	166	5.4E+00				20.00	5.2E+00	
5	20.30	4	5	255	4.2E+00				20.00	3.7E+00	
7	20.10	2	8	88	2.9E+00				20.00	2.8E+00	
8	20.20	2	10	80	2.6E+00				20.00	2.4E+00	
9	20.20	6	14	211	2.3E+00				20.00	2.1E+00	
10	20.20	10	22	281	1.8E+00				20.00	1.7E+00	
11	20.00	20	37	402	1.3E+00				20.00	1.3E+00	
12	19.90	40	67	657	1.1E+00				20.00	1.1E+00	
Test-81											
3	20.00	2	1	827	2.7E+01				20.00	2.7E+01	
4	20.10	2	3	445	1.5E+01				20.00	1.4E+01	
7	20.00	6	7	1121	1.2E+01				20.00	1.2E+01	
8	20.20	10	15	1341	8.8E+00				20.00	8.1E+00	
Test-82											
3	20.10	2	1	572	1.9E+01				20.00	1.8E+01	
4	20.20	2	3	328	1.1E+01				20.00	9.9E+00	
7	20.20	8	8	781	6.8E+00				20.00	6.3E+00	
8	20.10	9	16	411	3.2E+00				20.00	3.0E+00	
9	20.00	20	30	785	2.6E+00				20.00	2.6E+00	
Test-83											
3	20.00	2	1	212	6.9E+00	60	210	6.9E+00	20.00	6.9E+00	6.9E+00
4	20.10	2	3	71	2.3E+00	60	69	2.3E+00	20.00	2.2E+00	2.2E+00
7	20.20	6	7	195	2.1E+00	50	190	2.1E+00	20.00	2.0E+00	1.9E+00
8	20.00	10	15	167	1.1E+00	50	159	1.0E+00	20.00	1.1E+00	1.0E+00
9	20.00	20	30	153	5.0E-01	45	138	4.5E-01	20.00	5.0E-01	4.5E-01
11	20.00	40	60	185	3.0E-01	30	165	2.7E-01	20.00	3.0E-01	2.7E-01
12	20.00	80	120	178	1.5E-01	20	151	1.2E-01	20.00	1.5E-01	1.2E-01
14	20.30	160	240	173	7.1E-02	8	152	6.2E-02	20.00	6.4E-02	5.6E-02
15	20.00	260	450	81	2.0E-02	6	55	1.4E-02	20.00	2.0E-02	1.4E-02
17	20.10	60	610	18	2.0E-02	4	14	1.5E-02	20.00	1.9E-02	1.5E-02
18	20.10	60	670	16	1.7E-02	1	15	1.6E-02	20.00	1.7E-02	1.6E-02
Test-84											
3	19.90	2	1	331	1.1E+01				20.00	1.1E+01	
4	20.00	2	3	117	3.8E+00				20.00	3.8E+00	
7	20.10	6	7	269	2.9E+00				20.00	2.8E+00	
8	20.00	10	15	418	2.7E+00				20.00	2.7E+00	
9	20.00	20	30	457	1.5E+00				20.00	1.5E+00	
11-fail	20.20	40	60	749	1.2E+00				20.00	1.1E+00	
Test-85											
1	20.00	2	1	499	1.6E+01				20.00	1.6E+01	
2	20.00	2	3	452	1.5E+01				20.00	1.5E+01	
4	20.00	6	7	1161	1.3E+01				20.00	1.3E+01	
5	20.00	10	15	1038	6.7E+00				20.00	6.7E+00	
6-fail	19.90	10	25	685	4.5E+00				20.00	4.7E+00	
Test-86											
1	20.10	2	1	226	7.4E+00				20.00	7.1E+00	
2	20.00	2	3	123	4.0E+00				20.00	4.0E+00	
4	20.10	6	7	355	3.9E+00				20.00	3.7E+00	
5	20.10	10	15	337	2.2E+00				20.00	2.1E+00	
6	20.10	20	30	453	1.5E+00				20.00	1.4E+00	
7	20.10	40	60	609	1.0E+00				20.00	9.5E-01	
9-fail	20.20	60	110	800	8.7E-01				20.00	8.0E-01	
Test-87											
2	20.10	2	1	193	6.3E+00	100	190	6.2E+00	20.00	6.1E+00	6.0E+00
3	20.10	2	3	64	2.1E+00	85	61	2.0E+00	20.00	2.0E+00	1.9E+00
6	20.00	6	7	124	1.4E+00	55	119	1.3E+00	20.00	1.4E+00	1.3E+00
7	20.00	10	15	170	1.1E+00	45	163	1.1E+00	20.00	1.1E+00	1.1E+00
8	20.02	20	30	177	5.8E-01	35	165	5.4E-01	20.00	5.7E-01	5.4E-01
10	20.48	40	60	389	6.4E-01	25	372	6.1E-01	20.00	5.4E-01	5.2E-01
11	20.06	80	120	259	2.1E-01	25	226	1.8E-01	20.00	2.1E-01	1.8E-01
13	19.97	160	240	220	9.0E-02	15	180	7.4E-02	20.00	9.1E-02	7.4E-02
14	19.87	320	480	170	3.5E-02	5	143	2.9E-02	20.00	3.6E-02	3.1E-02
16	20.09	90	525	42	3.1E-02	3	38	2.7E-02	20.00	3.0E-02	2.6E-02
17	19.99	90	615	30	2.2E-02	2	27	2.0E-02	20.00	2.2E-02	2.0E-02

Note: Wind speed correction coefficient default = 0.15 (admixture), change to 0.18 for soil surfaces [coef. is used 4 times in columns k & l].

Test No.	Actual Wind Speed (m/s)	Δt (min)	t (avg.) (min)	ΔM admix (g)	Total Deflation (g/m ² -s)	Correction for ASMC			Correction for Wind Speed		
						Evap. Rate (g/hr)	ΔM soil (g)	Dry Mass Deflation (g/m ² -s)	Wind Speed (m/s)	Total Deflation (g/m ² -s)	Dry Mass Deflation (g/m ² -s)
Test-87											
18	19.97	90	705	27	2.0E-02	1	26	1.9E-02	20.00	2.0E-02	1.9E-02
Test-83											
20	20.16	10	705	4	2.6E-02				20.00	2.4E-02	
21	19.97	90	755	20	1.5E-02				20.00	1.5E-02	
BAR-88											
4	9.97	15	8	28	1.2E-01				10.00	1.2E-01	
5	15.03	2	1	75	2.5E+00				15.00	2.4E+00	
6	15.13	2	3	33	1.1E+00				15.00	1.0E+00	
BAR-89											
4	10.02	15	8	16	7.0E-02				10.00	6.9E-02	
5	20.00	2	1	1026	3.4E+01				20.00	3.4E+01	
6-fail	20.00	2	3	538	1.8E+01				20.00	1.8E+01	
BAR-90											
4	9.97	15	8	23	1.0E-01				10.00	1.0E-01	
5-fail	26.10	2	1	3531	1.2E+02				25.00	7.3E+01	
BAR-91											
4	10.03	15	8	24	1.0E-01				10.00	1.0E-01	
5	14.90	2	1	246	8.0E+00				15.00	8.4E+00	
6	15.11	2	3	145	4.7E+00				15.00	4.5E+00	
BAR-92											
4	10.05	15	8	35	1.5E-01				10.00	1.5E-01	
5	20.02	2	1	1707	5.6E+01				20.00	5.5E+01	
6-fail	20.09	2	3	947	3.1E+01				20.00	3.0E+01	
BAR-93											
4	10.00	15	8	29	1.3E-01				10.00	1.3E-01	
5	24.20	1	1	2382	1.6E+02				25.00	2.1E+02	
BAR-94											
2	10.02	15	8	44	1.9E-01				10.00	1.9E-01	
3	12.74	2	1	69	2.3E+00				15.00	5.8E+00	
4	15.05	2	1	307	1.0E+01				15.00	9.8E+00	
5-fail	25.20	1	1	2480	1.6E+02				25.00	1.4E+02	
BAR-95											
2	9.92	15	8	36	1.6E-01				10.00	1.6E-01	
3	20.10	2	1	1437	4.7E+01				20.00	4.5E+01	
BAR-96											
2a	10.01	2	1	36	1.2E+00				10.00	1.2E+00	
2b	9.91	15	8	44	1.9E-01				10.00	2.0E-01	
3	20.04	2	1	1353	5.1E+01				20.00	5.0E+01	
BAR-97											
2a	10.01	2	1	25	8.2E-01				10.00	8.1E-01	
2b	9.96	15	8	36	1.6E-01				10.00	1.6E-01	
3	20.11	2	1	2206	7.2E+01				20.00	6.9E+01	

Note: Wind speed correction coefficient default = 0.15 (admixture), change to 0.18 for soil surfaces [coef. is used 4 times in columns 9 & 11].

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