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Project Summary

Windbreak Effectiveness for Storage-Pile Fugitive-Dust Control: A Wind Tunnel Study

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Results of wind-tunnel experiments to determine the optimal size and location of porous windbreaks for controlling fugitive-dust emissions from storage piles in a simulated neutral atmospheric boundary layer are presented. Straight sections of windbreak material were placed upwind of two non-erodible, typically shaped piles and were also placed on the top of one of the piles. Wind speed, measured near the pile surface at various locations with heated thermistors, was isolated here as the primary factor affecting particle uptake. Wind speed distributions about the piles in the absence of any windbreak and the flow structure downwind of a three-dimensional porous windbreak are presented. Relative wind speed reduction factors are described and efficiencies based on the relationship between wind speed and particle uptake are given. The largest and most solid windbreak caused the greatest wind speed reduction, but similar wind speed reductions were obtained from several smaller windbreaks. A 50% porous windbreak of height equal to the pile height and length equal to the pile length at the base, located one pile height from the base of both piles was found to be quite effective in reducing wind speeds over much of the pile. Windbreaks placed on the top of a flat-topped pile caused large wind speed reductions on the pile top, but small, if any, reductions on the windward pile face. Windbreak effectiveness decreased as the angle between the windbreak and the wind direction decreased.

This Project Summary was developed by EPA's Atmospheric Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Fugitive dust fron sources such as storage piles, materi als transfer points, unpaved roads, and agricultural tilling contribute significantly to total suspended particulate (TSP) levels in some regions of the country. In addition to limits on ambient concentrations of TSP, radioactive particulate is also regulated. Early air pollution control efforts emphasized controlling emissions from stacks rather than fugitive-dust emissions because the greater bulk of pollutants came from stacks. Now, control methods for fugitive-dust emissions are also being tested.

Storage-pile fugitive-dust emission rates depend upon the stored material's bulk density, moisture content and particle size distribution, the storage pile geometry, the wind velocity near the pile surface and other parameters. However, particle uptake does not occur unless the wind speed is greater than a given value, the threshold velocity, which is dependent upon the type of stored material, its moisture content and particle size distribution. Several empirical relationships between wind speed and particle uptake rate are found in the literature. Particle uptake appears to be related to u^n, where n is between 1 and 3.

The use of windbreaks for storage-pile fugitive-dust control is based upon the existence of a sheltered region downstream of a windbreak. Wind tunnel and field experiments have shown that porous windbreaks produce large areas of reduced wind speed in their lee. As expected, the location of the sheltered region shifts as the wind direction varies from that of the windbreak normal.

In the present study, wind speed was isolated as the primary factor affecting particle uptake, although moisture content, particle size, and bulk density affect fugitive-dust emissions as well. Wind speed was measured near the pile surface with and without windbreaks of several sizes and porosities located various distances upwind or on the top of two typically shaped storage piles. No effort was made to simulate fugitive dust emissions. Effect of wind direction was also observed. The wind speed patterns were analyzed to determine the optimal windbreak porosity, height, length, and location and to develop windbreak design guidelines for storage-pile fugitive-dust control.

Experimental Design and Instrumentation

Experimental Design

The experiment was conducted in the EPA Meteorological Wind Tunnel. A neutrally stratified simulated atmospheric boundary layer was generated using a trip fence placed near the test section entrance. Gravel roughness composed of pebbles having typical diameters of 10 mm covered the tunnel floor downstream of the fence. The boundary layer was characterized by a depth of approximately 1 m, roughness length (z_0) of 0.12 mm, and friction velocity (u_*) of $0.048U_0$, where $U_0 = 4$ m/s is the free-stream speed.

Model size and free-stream wind speed should ideally be determined from matching the model and full-scale Reynolds numbers Re. However, with typical scale reductions, the model Re is much less than the full-scale Re, but the former is large enough for the flow structure to be described in terms of characteristic length and velocity scales, independent of Re. Since atmospheric flows are almost always aerodynamically rough (for all wind speeds), they are also Re-independent. Hence wind tunnel velocities, normalized by an appropriate scaling velocity, are equivalent to normalized full-scale values, provided the relevant length scale ratios are matched for geometric similarity.

Windbreak effects on two typical, but idealized, pile geometries are studied; the results may be applicable to similar full-scale piles. The piles modeled had the same height (11 m) and side slopes (37°), but different shapes, one a cone and the other an oval, flat-topped pile. The criterion of matching the ratio of the pile height to the surface roughness length was used to obtain the scaling ratio between the model and prototype of 1:100. The model surfaces were roughened to satisfy the roughness Reynolds number criterion for aerodynamically rough surfaces.

Windbreaks were constructed of synthetic materials of 50% and 65% porosity, which are commercially available and can be used in the field. Windbreaks of three heights and two lengths were placed at either of two distances upwind of the conical pile base. One windbreak was also placed at angles of 20° and 40° from the position normal to the incident flow. For the oval, flat-topped pile, the longer axis of the pile was normal to the airflow and parallel to the windbreak. The same windbreak porosities and relative sizes and positions were used, but additional tests were conducted with two more windbreak heights and one more length. The other windbreak locations tested were on the pile top, either close to the centerline or at the upstream edge of the pile top parallel to the pile's longer axis. Two heights and two lengths were tested. For windbreaks in both positions the pile was rotated 20° and 40° to simulate other wind directions.

The final phase of the project was to measure mean velocity and turbulence intensities downstream of the less porous windbreak oriented normal to the airflow to determine whether reverse flow was present and to determine the regions of reduced mean flow and enhanced turbulence.

Instrumentation

A hot-wire anemometer with a boundary-layer type cross-wire probe and a pulsed-wire anemometer were used to measure mean flow and turbulence intensity downstream of a windbreak. The pulsed-wire anemometer is used in regions where turbulence intensity is very high or flow reversal occurs; the pulsed-wire senses both wind speed and direction.

Heated Fenwal thermistors projecting out of the pile surface at various locations were used to measure wind speeds. Thermistor anemometers operate under the same basic principle as do hot-wire anemometers; that is, the heat loss from the sensor is a function of wind speed. The relationship between wind speed and heat loss was determined experimentally from calibration.

Flow About Porous Windbreak

Relative wind speed deficit due to a windbreak may be defined as $[U_R(z) - U(z)]/U_R(z)$, where $U_R(z)$ is the reference speed at the location of the windbreak but in its absence, and U(z) is a speed at some distance downstream of the windbreak. Lines of constant relative deficit are seen in Figure 1. Downstream distance and height were scaled by the windbreak height h. Below z = 1h, wind speeds were reduced at least 50% from the upstream value at the same height. The greatest reductions were observed for heights less than z = 0.5h between approximately 4 and 8h downstream. In other words, the maximum reduction did not occur immediately downstream of the windbreak, but occurred farther downstream. High turbulence intensity (the ratio of the rms fluctuating longitudinal velocity at a given location to the mean wind speed at that location) was observed in the low wind speed region, although high values of the fluctuating velocity extended downstream from the top of the windbreak.

Flow About Storage Piles

For the conical pile, the areas of maximum wind speed were near the top of the upwind face but toward the sides of the pile. A high speed region was on the upstream face, extending from near the crest down both sides. The area of minimum wind speed was in the lee. For normal incident flow to the oval pile, the highest wind speeds were observed on the windward face near the top of the pile, extending down the sides, similar to the case with the conical pile. Again, the lowest speeds were observed in the lee; but a secondary minimum also occurred on the top of the pile.

Windbreak Effects on Flow About Storage Piles

Initial guidance on the desired size of the windbreak and its location was obtained from an examination of the ob-

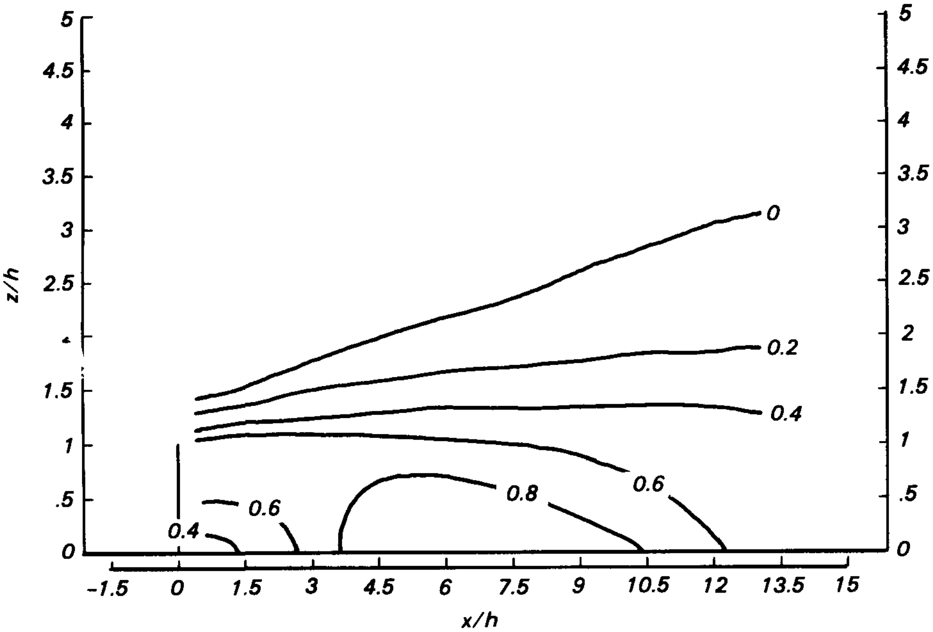

Figure 1. *Relative wind speed deficit downstream of a porous windbreak.*

served flow and sheltered region behind the windbreak in the absence of the pile. Since height and width of the sheltered region were directly related to windbreak height and length, windbreaks placed upstream of the pile having dimensions less than the pile height or length were expected to be less efficient, as were smaller windbreaks placed on the pile top. With a windbreak, the wind speed at a given location on the pile surface is some fraction of that in the unprotected case. The relative amount by which the wind speed is reduced is called the wind speed reduction factor R_i and, in percent, is defined as

$$R_i = (u_{o,i} - u_i)/u_{o,i} \times 100 \quad , \qquad (1)$$

where u_i and $u_{o,i}$ are wind speeds at the i-th location on the pile for the cases with and without the windbreak, respectively.

Contours of constant wind speed reduction resulting from windbreaks of different porosity, but height equal to the pile height and length equal to the length of the pile top (0.6B), located one pile height from the base of the pile are shown in Figure 2. The lower porosity windbreak gave greater wind speed reductions; reductions greater than 40% were observed for the 50% porous windbreak, but were not for the 65% porous windbreak. For a windbreak as long as the pile base, the high reductions extended to the pile sides. Windbreaks of height one half the pile height caused smaller reductions near the top of the pile and even caused wind speed increases in part of the lee of the conical pile and on the top of the oval pile. Windbreaks of height greater than the pile caused significantly higher reduction only on the top of the flat-topped pile. Higher windbreaks also tended to be more effective when located farther from the pile. Windbreak effectiveness decreased with increasing angle of flow from the normal.

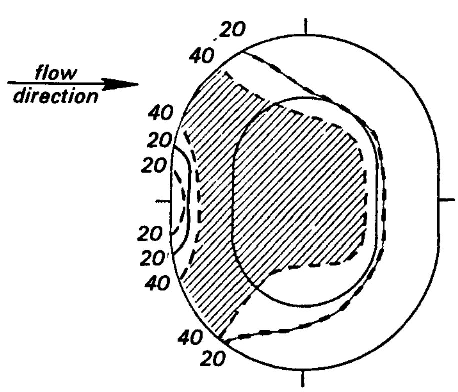

Figure 2. *Wind speed reduction factor for the windbreak of height 1.0H and length 0.6B placed 1 H from the oval, flat-topped pile base with porosity 65% (solid line) and 50% (dashed line).*

For windbreaks placed on the top of the oval, flat-topped pile, large reduction factors (up to 65%) on the pile top were observed. The location and extent of the area with significant wind speed reduction depended upon windbreak size, location, and angle of the incident flow. This suggests that fugitive-dust emissions on the top of the pile may be controlled locally through the use of a windbreak.

Relation to Particle Uptake

In terms of fugitive-dust emissions, the windbreak efficiency E may be defined as $E = -(Q/Q_o)$, where Q and Q_o are the storage-pile fugitive-dust emission rates with and without the windbreak, respectively. Since only surface wind speeds have been measured here, assumed relationships between wind speed and emissions are used to calculate efficiencies. To a first approximation, it was assumed here that the reference wind speed is sufficiently high that wind speeds everywhere, with and without a windbreak, exceed the threshold speed. An efficiency E_n can be defined based upon a given power-law relation between wind speed and particle uptake, $Q \propto u^n$ (where n is between 1 and 3). In effect, these efficiences are $1 - (\overline{u^n}/\overline{u_o^n})$, where $\overline{u_n}$ and $\overline{u_o^n}$ are the area-averaged values over the pile surface with and without a windbreak, respectively. A better definition of efficiency would include a threshold wind speed, but the relationship between threshold speed and particle type, size and moisture content is not well understood. Efficiencies E_1 and E_3 are calculated here, using values of $n = 1$ and 3.

E_1 for the windbreaks placed upstream of the conical and larger piles with normal incident flow are given in Tables 1 and 2, respectively. In general, a windbreak was more effective (higher E_1) when placed upstream of the conical pile, as compared to a windbreak of the same relative size placed upstream of the larger, oval-shaped pile. Trends in E_1 with changes in height, length, location and porosity of the windbreak were similar for both piles. In general, a windbreak at least as high as the pile is desirable. The 1.5H height was slightly more effective than the 1.0H height with the oval, flat-topped pile, reflecting increased wind speed reductions on the pile top for the highest windbreak. Efficiencies were higher for the less porous windbreak material. Except for the windbreaks of height one half the pile

Table 1. *Efficiency (E_1) for the Various Windbreaks Placed Upstream of the Conical Pile*

	65% porous windbreak				*50% porous windbreak*			
position:	*1H*		*3H*		*1H*		*3H*	
length: / *height*	*1.0D*	*1.5D*	*1.0D*	*1.5D*	*1.0D*	*1.5D*	*1.0D*	*1.5D*
0.5H	*34*	*32*	*28*	*30*	*46*	*45*	*36*	*36*
1.0H	*48*	*45*	*53*	*52*	*66*	*67*	*65*	*71*
1.5H	*47*	*44*	*55*	*54*	*64*	*65*	*71*	*77*

Table 2. *Efficiency (E_1) for the Various Windbreaks Placed Upstream of the Oval, Flat-Topped Pile*

	65% porous windbreak				*50% porous windbreak*				
position:	*1H*		*3H*		*1H*			*3H*	
length: / *height*	*0.6B*	*1.0B*	*0.6B*	*1.0B*	*0.6B*	*1.0B*	*1.5B*	*0.6B*	*1.0B*
0.5H	*15*	*16*	*13*	—	*18*	*20*	*21*	*15*	*17*
0.75H	—	—	—	—	—	*41*	—	—	*34*
1.0H	*27*	*34*	*28*	*37*	*34*	*53*	*51*	*31*	*49*
1.25H	—	—	—	—	—	*56*	—	—	*57*
1.5H	*33*	*39*	*38*	—	*44*	*58*	*59*	*43*	*62*

height (0.5H), efficiency was lower when the windbreak was not as long as the pile base length.

Trends in the values of E_3, the efficiency based upon the u^3 relation to dust uptake, with windbreak height, length, location and porosity were found to be similar to those for E_1, except the values of E_3 were considerably larger than those of E_1 (see Figure 3).

Although the highest efficiencies (E_3) of 99% and 96% corresponded to the 50% porous material of height 1.5 times the pile height (H), length 1.5 times the base diameter of the conical pile and equal to the base length of the oval, flat-topped pile, respectively, located 3H from the base of the piles, the efficiencies of the more economical windbreak of the same porosity, height equal to the pile height and length equal to the pile base length were only slightly lower (97% and 89%, respectively). Clearly, the latter size would be preferable on the basis of cost effectiveness. Any location between 1H and 3H from the base of the pile could be chosen depending on the convenience.

Conclusions

This wind tunnel study has shown that windbreaks normal to the wind direction placed upwind of a conical and a larger, oval, flat-topped storage pile reduce wind speeds near the surface of the pile and hence suggest reductions in fugitive-dust emissions. Of the windbreaks tested for each pile, the largest 50% porous windbreak placed 3H from the pile appears to be best in terms of greatest wind speed reductions and effectiveness for fugitive-dust control. However, all the 50% porous windbreaks at least as high as the pile and as long as the pile base had similar overall effects. Windbreaks of height and/or length less than that of the pile were clearly less effective. Optimal windbreak location appears to be related to windbreak height, particularly for the conical pile; the higher the windbreak, the farther it should be located upwind of the pile. However, locations farther than 3H were not examined.

Windbreak length and position are even more important in determining effectiveness when the airflow is not normal to a windbreak. With a windbreak of height and length equal to the pile dimensions, fairly high wind speed reductions resulted when the windbreak was placed upwind normal to the flow and also at an angle of 20° to the normal, but very little reduction occurred at an angle of 40°.

Windbreaks placed on the top of the oval, flat-topped pile caused large areas of significant wind speed reductions on the pile top, both downwind and upwind of the windbreak, but very small reductions to the high wind speeds on the windward face. The area of greatest reduction was not immediately downwind of the windbreak, but displaced farther downstream. Changes in wind direction shifted the location of the sheltered region. These results suggest that fugitive-dust emissions may be locally controlled with windbreaks placed on the top of a relatively level storage pile. In particular, portable windbreaks may be quite practical since they could be positioned to protect active areas of the pile.

Wind speed was isolated here as the major factor affecting storage-pile fugitive-dust emissions, but storage-pile moisture content, type of material stored and threshold wind speed also affect emissions. A clearer understanding of the relationship of wind speed and threshold speed to fugitive-dust emissions would allow for better analysis of the data presented. Additional field measurements of fugitive dust from storage piles with and without windbreaks would be helpful for comparison to the efficiencies and design guidelines presented here.

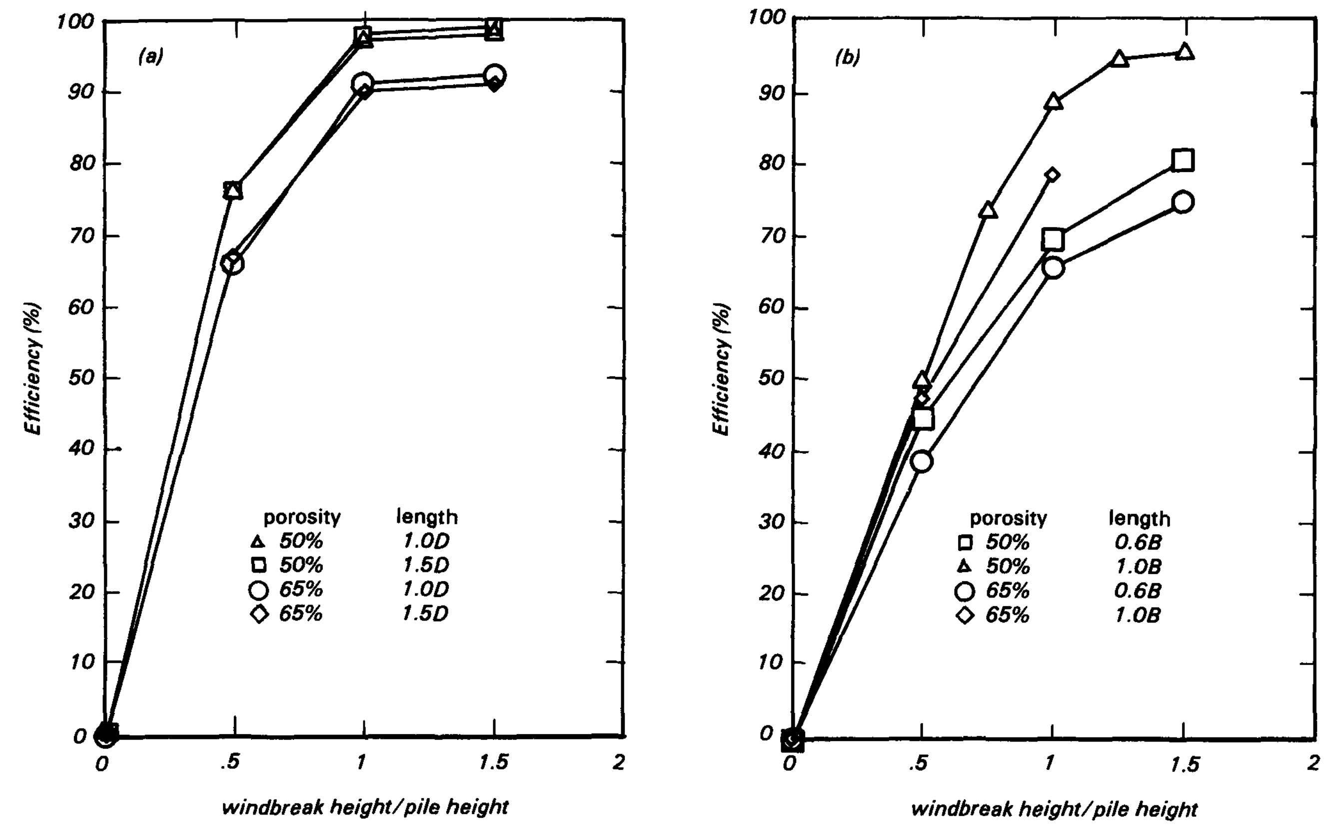

Figure 3. *Efficiency (E_3 vs. height for windbreaks placed 3H from the pile base: (a) conical pile, (b) oval, flat-topped pile.*

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The complete report, entitled "Windbreak Effectiveness for Storage-Pile Fugitive-Dust Control: A Wind Tunnel Study," (Order No. PB 85-243 848/AS; Cost: $16.95, subject to change) will be available only from:
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