Fly ash erodibility

Gary A. Lehrsch and Dale E. Baker

ABSTRACT: In the northeastern United States, fly ash is removed from stack gases and commonly trucked to landfills for disposal. The cover soil and especially the underlying fly ash of these landfills are susceptible to erosion by water. Fly ash erodibility was estimated by collecting sediment eroded by natural rainfall in the field from standard erosion plots (1.8 m wide and 22.1 m long on a 9% slope of exposed fly ash). The universal soil loss equation (USLE) was used with direct measurements on-site to obtain estimates of the erodibility factor, K, for fly ash. These estimates were then compared to an estimate obtained using a soil erodibility nomograph. The K factors measured in the field ranged from 0.11 to 0.13 Mg ha h (ha MJ mm)$^{-1}$ and averaged 0.122 Mg ha h (ha MJ mm)$^{-1}$. A K factor of 0.122 Mg ha h (ha MJ mm)$^{-1}$ was recommended for erosion control. With this K factor and the USLE, the surface topography of vegetated fly ash disposal areas was designed to limit soil loss to a tolerance level of 4.5 Mg (ha y)$^{-1}$. Using the design K factor, erosion from vegetated demonstration plots, 73 m long on a 15% slope, was controlled.

FLY ash consists of finely divided particles of ash removed from the stack gases of coal-fired, electric-generating power plants. Fly ash production in the United States in 1986 was 45×10^6 Mg (49.6 million tons) (2). With use accounting for less than 18% of the ash produced, about 37×10^6 Mg (40.8 million tons) of fly ash remained for disposal. Fly ash in such quantities, unless properly disposed of, can become a significant environmental hazard.

Gary A. Lehrsch, formerly a graduate student in the Department of Agronomy, Pennsylvania State University, is now a soil scientist with the Soil and Water Management Research Unit, Agricultural Research Service, U.S. Department of Agriculture, Kimberly, Idaho 83341. Dale E. Baker is a professor of soil chemistry in the Department of Agronomy, Pennsylvania State University, University Park, 16802. *Authorized for publication as Journal Series Paper No. 7636 of the Pennsylvania Agricultural Experiment Station, University Park. The authors thank the Pennsylvania Electric Company for providing financial support for the study and K. C. McGregor and R. L. Cunningham for reviewing the manuscript.* *Trade names are included for the benefit of the reader and do not imply endorsement of or preference for the product by Pennsylvania State University or the U.S. Department of Agriculture.*

The susceptibility of fly ash to water erosion is termed fly ash erodibility. Because fly ash is eroded easily by water, fly ash disposal areas can be unstable (*4, 9*). On steep slopes, especially those with little or no vegetative cover, erosion, including gullying, can be extensive.

The erodibility of a soil or waste material, such as fly ash, depends upon both its physical and chemical properties. A nomograph that requires selected soil properties as input (*16*) has been used extensively to estimate the erodibility of soil and soil-like materials. Young and Mutchler (*19*), studying Minnesota soils, and Stein and associates (*14*), studying reclaimed strip-mined soils, found that nomograph estimates were, for the most part, lower than the estimates obtained from direct field measurements. In a study on the erosion of spoil banks, McKenzie and Studlick (*11*) also found that the nomograph's estimates of the K factor were lower than the estimates obtained by direct measurement on the spoil banks. For the reclaimed soils and spoil, gully erosion, though not mentioned by the authors, may have been responsible wholly or in part for the direct measure-

Reprinted from the Journal of Soil and Water Conservation
November-December 1989, Volume 44, Number 6

ments being higher than the nomograph estimates.

Direct field measurement is a more involved but more accurate method for determining the erodibility factor for soils. This technique has been used to measure the erodibility of spoil banks and subsoils by McKenzie and Studlick (*11*) and Roth and associates (*13*), respectively. Most commonly, long-term average K-factor values measured using this procedure range from 0.026 to 0.053 Mg ha h (ha MJ mm)$^{-1}$ (*17*). The highest reported long-term average erodibility factor is 0.091 Mg ha h (ha MJ mm)$^{-1}$ for Dunkirk silt loam (fine-silty, mixed, mesic Glossoboric Hapludalf) in Geneva, New York (*17*).

Although erodibility factors have been reported for soils and some spoil materials, no erodibility factor has been published for fly ash. Even though water erosion of fly ash is a potentially serious problem (*1, 6, 10, 15*), little if any research has been conducted to quantify the susceptibility of fly ash to erosion.

We sought to estimate a fly ash erodibility factor, K, by measuring the erosion of fly ash in the field, that is, on a fly ash disposal site. We then compared the field estimate to one obtained using the standard nomograph (*16*). Finally, demonstration plots that managed to control the erosion of fly ash were evaluated to determine the effectiveness of the K factor.

Background

Wischmeier and Smith (*17*) developed the universal soil-loss equation (USLE), A=RKLSCP, where A is the soil loss in mass per unit area from both sheet and rill erosion, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover management factor, and P is the supporting practices factor. The USLE is an empirical equation designed to estimate average erosion rates over time, usually 1 year.

The erosivity factor, R, in the USLE accounts for the erosivity of raindrop impact and surface runoff from rainfall. The R factor for a single storm (*17*) is the product of the total energy of the storm, E, and the storm's maximum 30-minute rainfall intensity, I_{30}, as follows:

$$R=EI_{30} \qquad [1]$$

where R is the rainfall factor [MJ mm (ha h)$^{-1}$], E is the total storm energy (MJ ha^{-1}), and I_{30} is the maximum 30-minute rainfall intensity (mm h^{-1}).

The energy of a rainstorm is a function of both the amount of rain and its intensity. The unit energy of falling rain (*5, 17*) is given as follows:

$$E_{inc}=0.119+0.0873 \log (I_{inc}) \qquad I_{inc} \leq 76 \text{ mm h}^{-1} \qquad [2]$$

$$E_{inc}=0.283 \qquad I_{inc}>76 \text{ mm h}^{-1} \qquad [3]$$

where E_{inc} is the kinetic energy of the storm increment [MJ (ha mm)$^{-1}$] and I_{inc} is the rainfall intensity of the storm increment (mm h^{-1}).

The relation of soil loss to EI_{30} is considered linear. Therefore, total erosivity for a period is the sum of EI_{30} for the individual storms (over 13 mm unless at least 6 mm of rain fell in 15 minutes) that occurred during the period. Thus, average annual R values for specific localities (*17*) are simply the average annual totals of the storm EI_{30} values.

Study methods

We measured fly ash erodibility in the field. By definition, the K factor is the rate of erosion per unit of erosion index (EI_{30}) from fallow unit plots [22.1 m (72.5 feet) long, 1.8 m (5.9 feet) wide] with a uniform slope of 9% and no conservation practices in use (*17*). Earth-moving equipment placed fly ash at a 9% slope in 0.6-m (2-foot) layers and compacted each fly ash layer using procedures common in fly ash placement. Two unit plots were established side by side on this sloping area. Tillage using a rototiller was performed parallel to the slope at about 4-week intervals to maintain the plot surfaces in continuous fallow and to destroy surface crusts. From each of these unit plots we collected all runoff and sediment (suspended fly ash) in 400-liter (105-gallon) livestock watering tanks.

We used a weighing bucket-type recording rain gauge about 18 m (59 feet) from the unit plots to measure rainfall intensities and amounts during the study. From this information we determined the total storm energy (by summing the energy contributions of specific quantities of rain falling at constant intensities) and the maximum 30-minute rainfall intensity of every runoff-producing storm.

The erosion plots were in operation during the summer and early fall of both 1978 and 1979. During this period, nine rainstorms of 13 mm (0.5 inch) or more occurred. After each runoff event, the volume of runoff in each stock tank was measured and the runoff was mixed to place the fly ash in suspension. We then took two representative samples of either 500 or 1,000 ml (17 or 34 ounces). Mixing was difficult. Though we made every effort to mix the fly ash evenly in the runoff, the fly ash concentration among duplicate runoff samples taken from the same stock tank from each storm still had a standard deviation of 17,000 mg l^{-1} (17,000 parts per million) of water. After sampling, the runoff in the stock tanks was discarded and the tanks were cleaned in preparation for the next runoff-producing storm event. The two representative runoff samples were then taken to the laboratory where the fly ash concentration was determined by drying two 100-ml subsamples at 105°C.

We then calculated estimates of fly ash erodibility. Under the conditions of this experiment, the LS, C, and P terms in the USLE have values of unity. Erodibility is thus

$$K=(\Sigma A)/(\Sigma R) \qquad [4]$$

We calculated fly ash erodibility for each plot by substituting into equation 4 the values for A and R summed over the 10 months that the erosion plots were in operation.

We also used the USLE erodibility nomograph (*16*) to obtain an estimate of fly ash erodibility. We determined a particle size distribution for fly ash using the hydrometer method (*3*). The saturated hydraulic conductivity of fly ash was measured (*8*) on 7.6-cm (3-inch) diameter cores, 7.6 cm long, taken from the upper 15 cm (6 inches) of the fly ash on the disposal site of the Conemaugh Electric Power Generating Station at Seward, Pennsylvania. Because we assumed the carbon content of the fly ash was negligible (*1*), the organic matter content of the fly ash was taken to be zero. Lastly, the structure of the fly ash on the disposal site was determined to be massive.

Results

Before the K factors were determined, we calculated the rainfall erosivity factors, R, for each of the storms using equation 1. Table 1 shows the R factors and other characteristics of each storm that occurred during the 2-year study period. The R values varied by a factor of more than 23, showing that storms of quite different erosivities were represented in the data.

Figure 1 shows each erosion plot's soil loss from each of the storms. The correlation coefficient relating soil loss to R was +0.74 for plot 1 and +0.72 for plot 2, both significant at the 5% level. For the same storm, the erosion rate from plot 2 often exceeded that from plot 1, even by as much as 25 Mg ha^{-1} (11 tons/acre) (Table 1). Plot-to-plot variation in field-measured erosion rates is common and is caused by factors beyond the control of the researcher (K. C. McGregor, 1989, personal communication; L. D. Meyer, 1987, personal communication).

Several factors may have been responsible for the variation in erosion from plot to plot. Some of this variability may have been caused by air-filled porosity differences caused by differential settling or compaction of the fly ash. These variations in porosity would have affected infiltration from plot to plot that, in turn, would have caused different runoff rates. Variation was likely because of rilling that occurred differently on the two plots.

Some variability also may have been caused by errors in sampling the storm runoff. If 300 l (79 gallons) of runoff were assumed for each storm, the standard deviation among measurements of the sediment concentration was equivalent to a difference in soil loss of 1.26 Mg ha^{-1} (0.56 tons/acre).

Pozzolanic (age-related) hardening of the fly ash (*7*) could have caused variation in erosion rates as well. Pozzolanic hardening occurs over time when water in a fly ash deposit reacts with calcium hydroxide in the ash to form cement-like compounds. Surface crusting from pozzolanic hardening of the fly ash occurred to various degrees both in space and in time between the rototilling operations. Such variations in the fly ash surface could have caused different amounts of sediment to be eroded from each plot even when the same storm was responsible for the erosion.

We then estimated an erodibility (K) factor for fly ash. First, we used the nomograph (*16*). The fly ash in our plots consisted of 92% silt plus very fine sand (particles with diameters 0.002 to 0.1 mm), 6% sand (0.1 to 2.0 mm), and 2% clay (<0.002 mm). We assumed the fly ash contained no organic matter and was structureless, massive. Its saturated hydraulic conductivity was 0.14 cm h^{-1} and thus classified as slowly permeable. When these input parameters were used with the nomograph, with some extrapolation beyond the figure boundaries, the K factor was 0.108 Mg ha h (ha MJ $mm)^{-1}$. This value is more than twice that of a typical K for a highly erodible soil, 0.05 Mg ha h (ha MJ $mm)^{-1}$.

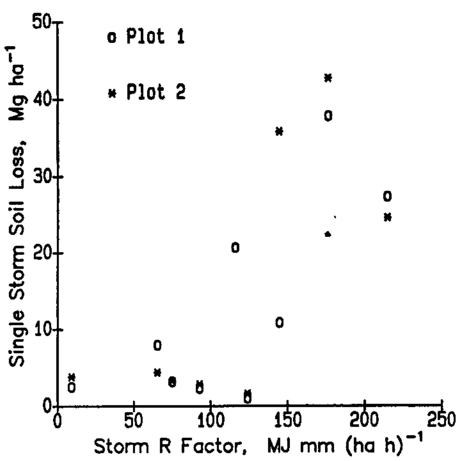

Figure 1. Single-storm soil loss from each erosion plot as a function of storm R factor.

Table 1. Storm characteristics and measured erosion rates.

Storm Date	*Erosion Plot*	*Total Rainfall (mm)*	*Maximum 30-minute Rainfall Intensity (mm h^{-1})*	*R* [MJ mm (ha $h)^{-1}$]	*A* (Mg ha^{-1})
6-27-78	1	22.3	21.8	115.7	20.7
9-19-78	1	22.1	39.6	215.1	27.3
9-19-78	2	22.1	39.6	215.1	24.6
8-11-79	1	38.6	16.3	124.1	1.0
8-11-79	2	38.6	16.3	124.1	1.6
8-21-79	1	20.1	18.3	74.9	3.2
8-21-79	2	20.1	18.3	74.9	3.3
8-26-79	1	24.9	27.4	144.6	10.8
8-26-79	2	24.9	27.4	144.6	35.8
9-02-79	1	31.0	24.4	176.7	37.8
9-02-79	2	31.0	24.4	176.7	42.7
9-05-79	1	46.7	11.2	92.8	2.3
9-05-79	2	46.7	11.2	92.8	2.8
10-02-79	1	18.8	16.3	65.2	7.9
10-02-79	2	18.8	16.3	65.2	4.4
10-09-79	1	12.7	4.6	9.2	2.5
10-09-79	2	12.7	4.6	9.2	3.8

Second, we used the data from table 1 to calculate fly ash erodibility (Table 2). This mean K factor of 0.122 Mg ha h (ha MJ $mm)^{-1}$ was larger than the nomograph estimate, 0.108 Mg ha h (ha MJ $mm)^{-1}$. Others (*11, 14, 19*) also have found soil and spoil K factors measured on-site to exceed nomograph estimates.

Discussion

The variation in the measured single-storm soil loss rates for the two plots (Table 1 and Figure 1) somewhat limits the confidence in the site estimate, 0.122 Mg ha h (ha MJ $mm)^{-1}$. A longer study could improve the estimate. However, the field-measured erosion rates (Table 1) unmistakably show that considerable ash was eroded by the storms that occurred throughout the study. Also, before this study began, fly ash was observed on the site to be extremely susceptible to erosion when thunderstorms occurred. Thus, this relatively high erodibility factor for fly ash may be appropriate.

The mean K factor value reported (Table 2) is higher than any erodibility factor known for a soil. Nevertheless, this higher K value is reasonable, considering the parameters that Wischmeier and his coworkers (*16, 18*) found to determine erodibility. This experiment's fly ash was very high in silt plus very fine sand, 92%. Soils with high percentages of such particles are the most erodible (*16, 18*). The ash studied also contained only 6% sand-sized particles. Most soils and even other fly ashes (*7*) contain higher percentages of sand. Negligible organic matter was present in the fly ash. Organic matter, when present, aids in aggregate stabilization thereby decreasing soil erodibility. Runoff was common because the fly ash had no structure, was only slowly permeable, and underwent pozzolanic hardening between each rototilling of the plot surfaces.

While the site estimate of the K value, 0.122 Mg ha h (ha MJ $mm)^{-1}$(Table 2), was 13% greater than the nomograph estimate, 0.108 Mg ha h (ha MJ $mm)^{-1}$, it was nonetheless of the same order of magnitude. Moreover, when one considers the quite different techniques used to obtain the estimates, the agreement is good (K.C. McGregor, 1989, personal communication). The nomograph estimate was, in fact, within one standard deviation of the site estimate (Table 2).

From society's viewpoint, extensive environmental damage and financial expense could occur if fly ash is disposed of improperly. Although fly ash disposal areas usually are covered with some depth of soil as a final cover, the erodibility of the fly ash is the critical factor as erosion into the underlying fly ash would degrade the environment. Such erosion would also be a financially serious problem for the electric utility to address. Fly ash erosion must be kept at or below 4.5 Mg (ha $y)^{-1}$ (2 tons/acre/year) (*17*) to protect the environment and safeguard the electric utility from legal action. Based upon the results of this experiment, a fly ash K factor of 0.122 Mg ha h (ha MJ $mm)^{-1}$ is recommended for erosion control.

Application

We used the USLE with the K factor of 0.122 Mg ha h (ha MJ $mm)^{-1}$ to obtain

Table 2. Fly ash erodibility (K) factor for design.

Parameter	Value*
Sample size	2
Mean	0.122
Standard deviation	0.014
Fly ash K factor for design	0.122

*K factor units are Mg ha h (ha MJ $mm)^{-1}$.

slope lengths and slope steepnesses that would limit annual erosion to 4.5 Mg ha^{-1} with an average annual R of 1957 MJ mm $(ha\ h)^{-1}$ at the Conemaugh disposal area (*17*). We used a C factor of 0.004 corresponding to an established meadow of a recommended grass-legume mixture (*12*). If no other conservation practices were used, the following combinations of slope length and steepness were calculated: 41 m (135 feet) and 20%, 106 m (348 feet) and 15%, and 210 m (689 feet) and 12%.

As a demonstration, plots 73 m (240 feet) long on a 15% slope were established in 1980 on both fly ash and fly ash covered with 8 to 15 cm (3-6 inches) of soil material. Though demonstration plots longer than 73 m were desired, they could not be constructed with the heavy equipment available at the disposal site. The area was hydroseeded and mulched with 6.8 Mg ha^{-1} (3 tons/acre) of wheat straw tacked with 34 kg ha^{-1} (30 pounds/acre) of asphalt (*12*). During the critical period before the grasses and legumes became established, some gullying occurred on the fly ash surface beginning 52 m (170 feet) from the top of the slope. Only minimal erosion, however, occurred within the first 41 m (135 feet). The vegetation grew quickly and erosion downslope was controlled. Thereafter, no severe rilling was seen and no deposition of fly ash was evident at the foot of the slope. The demonstration thus showed that vegetatively protected slopes at least 73 m long and with a steepness of 15% would resist erosion. Thus, the fly ash K factor could be somewhat less than 0.143 Mg ha h $(ha\ MJ\ mm)^{-1}$, corresponding to a slope length and steepness of 73 m and 15%. The recommended K factor, 0.122 Mg ha h $(ha\ MJ\ mm)^{-1}$, therefore, appears reasonable. The vegetative cover on the demonstration plots effectively controlled erosion for 7 years before it was intentionally removed.

Conclusions

The nomograph estimate of fly ash erodibility was 0.108 Mg ha h $(ha\ MJ\ mm)^{-1}$ and the estimate from field studies was 0.122 Mg ha h $(ha\ MJ\ mm)^{-1}$. These K factors reveal the extreme susceptibility of fly ash to erosion. Because fly ash is highly erodible, fly ash disposal areas are potentially serious problems to both society and electric utilities. Accordingly, a fly ash K factor of 0.122 Mg ha h $(ha\ MJ\ mm)^{-1}$ is recommended to control erosion on fly ash disposal areas.

REFERENCES CITED

1. Adriano, D. C., A. L. Page, A. A. Elseewi, A. C. Chang, and I. Straughan. 1980. *Utilization and disposal of fly ash and other coal residues in terrestrial ecosystems: A review.* J. Environ. Qual. 9: 333-344.
2. American Coal Ash Association, Inc. 1986. *Ash production ash utilization—1986.* Washington, D.C.
3. Day, P. R. 1965 *Particle fractionation and particle-size analysis.* In C. A. Black [ed.] *Methods of Soil Analysis. Part 1.* Am. Soc. Agron., Madison, Wisc. pp. 545-567.
4. DiGioia, A. M., J. E. Niece, and R. P. Hayden. 1974. *Environmentally acceptable coal-ash disposal sites.* Civil Eng. 44: 64-67.
5. Foster, G. R., D. K. McCool, K. G. Renard, and W. C. Moldenhauer. 1981. *Conversion of the universal soil loss equation to SI metric units.* J. Soil and Water Cons. 36: 355-359.
6. Golden, D. M. 1983. *Water pollution arising from solid waste (coal, fly ash, slag) disposal, and measures to prevent water pollution.* Water Sci. Tech. 15(11): 1-10.
7. Gray, D. H., and Y. K. Lin. 1972. *Engineering properties of compacted fly ash.* Am. Soc. Civil Eng. J. Soil Mechanics and Foundations Div. 98: 361-380.
8. Klute, A. 1965. *Laboratory measurement of hydraulic conductivity of saturated soil.* In C. A. Black [ed.] *Methods of Soil Analysis. Part 1.* Am. Soc. Agron., Madison, Wisc. pp. 210-221.
9. Lehrsch, G. A. 1979. *Controlling water pollution from fly ash disposal areas.* M. S. Thesis, Dept. Agron., Pa. State Univ., University Park.
10. Macyk, T. 1981. *Revegetation studies on fly ash and overburden at Grande Cache.* In P. F. Ziemkiewicz, R. Stein, R. Leitch, and G. Lutwick [eds.] *Coal Ash and Reclamation, Edmonton, Alberta.* Rpt. RRTAC 81-3. Alberta Land Cons. and Reclam. Council, Edmonton. pp. 116-126.
11. McKenzie, G. D., and J. R. Studlick. 1979. *Erodibility of surface-mine spoil banks in southeastern Ohio—an approximation.* J. Soil and Water Cons. 34: 187-190.
12. Pannebaker, F. A. 1978. *Chemical monitoring of soils and wastes for the establishment of vegetative cover on a fly ash disposal area.* M. S. thesis. Dept. Agron., Pa. State Univ., University Park.
13. Roth, C. B., D. W. Nelson, and M.J.M. Romkens. 1974. *Prediction of subsoil erodibility using chemical, mineralogical, and physical parameters.* EPA 660/2-74-043. U.S. Govt. Printing Off., Washington, D.C.
14. Stein, O. R., C. B. Roth, W. C. Moldenhauer, and D. T. Hahn. 1983. *Erodibility of selected Indiana reclaimed strip mined soils.* In Proc., 1983 Symp. on Surface Mining, Hydrology, Sedimentology and Reclamation. Univ. of Ky., Lexington. pp. 101-106.
15. Wallace, A., and G. A. Wallace. 1986. *Enhancement of the effect of coal fly ash by a polyacrylamide soil conditioner on growth of wheat.* Soil Sci. 141: 387-389.
16. Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. *A soil erodibility nomograph for farmland and construction sites.* J. Soil and Water Cons. 26: 189-193.
17. Wischmeier, W. H., and D. D. Smith. 1978. *Predicting rainfall erosion losses—a guide to conservation planning.* Agr. Handbk. 537. U.S. Dept. Agr., Washington, D.C.
18. Wischmeier, W. H., and J. V. Mannering. 1969. *Relation of soil properties to its erodibility.* Soil Sci. Soc. Am. Proc. 33: 131-137.
19. Young, R. A., and C. K. Mutchler. 1977. *Erodibility of some Minnesota soils.* J. Soil and Water Cons. 32: 180-182. □