Fine Particulates (PM10 and PM2.5) Generated by Breakage of Mobile Aggregates During Simulated Wind Erosion

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Abstract. *Wind erosion of soils generates fine particulates that are health hazards (PM10 and PM2.5) by three major processes: entrainment (emission) of loose mobile aggregates from the surface, abrasion from immobile clods/crusts, and breakage of mobile saltation/creep aggregates. To improve prediction of PM10 generation in erosion models, parameters must be established for these processes. The objectives of this research were to measure relative breakage fractions of saltation-size aggregates to suspension-size and the fractions of PM10 and PM2.5 generated by the breakage process for a range of soils. Soil samples were collected from nine states (Arizona, California, Nevada, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas). Sub-samples of the soils were used to determine organic matter and calcium carbonate fractions. Other sub-samples were dispersed to determine sand, silt, and clay fractions. The breakage process was simulated in the laboratory by repeated impacts of saltation-size aggregates in an enclosed chamber. Relative breakage fractions averaged 0.044 for aggregates with saltation-size sand/clay ratios between 0.1 and 10. Fractions for aggregates with either large clay or saltation-size sand fractions were significantly less, averaging 0.015. The fraction of PM10 in the suspension component created by breakage ($SF10_{bk}$) averaged 0.049 over all soils. The $SF10_{bk}$ was inversely proportional to both clay content and annual precipitation. Average $SF10_{bk}$ was 0.069 with clay fraction <0.1, but significantly lower (0.030) with clay fraction >0.1. The average ratio of PM2.5/PM10 was 0.154, but increased with saltation-size sand/clay ratio and decreased with precipitation. The predicted values ranged from about 0.1 to 0.3 (R^2 = 0.53).*

Keywords. *Breakage, Dust, Particulate, PM10, PM2.5, Wind erosion.*

Wind erosion occurs over a range of surface conditions, which causes wide variation in the downwind saltation and creep discharge (Fryrear et al., 1998). Field measurements also show that, even with similar saltation discharges, vertical dust flux varies widely among soils (Gillette, 1977). The combined saltation/creep mode of transport has a distinct transport capacity for each surface, based on the surface roughness and wind speed (Greeley and Iversen, 1985). In contrast, the suspension discharge typically increases downwind over the whole field and does not reach transport capacity on most eroding fields. As part of the suspension discharge, wind erosion contains fine particles (PM10 and PM2.5) that are health hazards (Ostro et al., 1999). PM10 and PM2.5 are defined as particulate matter less than 10 µm and 2.5 µm in aerodynamic diameter, respectively.

To aid in delineating erosion rates among various surfaces, we identified several erosion processes that act collectively to control erosion rates (Hagen, 1995). The major processes include direct entrainment (emission) of loose soil by wind and/or saltation impacts, creation of additional mobile soil by abrasion of immobile clods/crust by saltation impacts (Hagen, 1991; Hagen et al., 1992), and breakage of mobile saltation/creep-size aggregates to suspension size. These same processes also control generation of PM10 and PM2.5 during wind erosion.

The terminology applied to describe the various erosion processes often varies among authors (e.g., Chandler et al., 2002; Hagen et al., 1999). However, based on our preceding definition of abrasion, it follows that the abrasion process would not occur on an entirely mobile surface that lacked immobile clods or crust. The term breakage is generally used to denote size reduction of mobile particles or aggregates by impacts (Ghadiri, 1997), but in this work it is further restricted to mean a size reduction from saltation/creep size (>100 µm diameter) to suspension size (≤100 µm diameter).

The major wind erosion processes have been formulated into separate, but linked, differential equations that predict the downwind saltation/creep, suspension, and PM10 erosion discharge (Hagen et al., 1999). To reduce computer run time for the Wind Erosion Prediction System (WEPS) model, analytic solutions also were developed for the prediction equations. Separating the erosion discharge components is useful because they differ in responses to the wind driving force and also in potential off-site impacts.

However, practical application of WEPS, as well as most other models, for prediction of PM10 and PM2.5 requires estimates of a number of parameters that are related to the PM10 generation processes. These parameters include the

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reservoir of loose PM10 in the surface soil created by weathering and mechanical forces, fractions of PM10 in suspension components created during erosion events by abrasion ($SF10_{an}$) and breakage ($SF10_{bk}$), and the ratios of PM2.5 to PM10 loose in the soil or created during abrasion and breakage.

Researchers are beginning to provide initial values of these parameters in relation to intrinsic soil properties and source location. From a sieving study, loose particle fraction less than 10 μm diameter in 11 Kansas soils ranged from 0.05% (Smolan silty clay loam) to 0.39% (Carr sandy loam), averaged over four years of sampling (Mirzamostafa, 1996). Slightly larger PM10 amounts were reported for a range of California soils when a fluidized bed of the soil fraction less than 2.0 mm diameter was used to suspend loose PM10 with a minimum of soil breakage (Carvacho et al., 2001). In the California soils, loose PM10 content ranged from about 0.25% to 0.42%. When only the soil fraction less than 75 μm was tested in the fluidized bed, the loose PM10 content increased and ranged from 0.68% to 1.9%. Resuspension tests of soils from the Columbia Plateau in Washington revealed that loose PM10 was generally larger than in California soils and ranged from 0.2% to 1.1% of the soil fraction less than 2.0 mm in diameter (Chandler et al., 2002).

Emission of loose material typically dominates the erosion process on small areas, such as city lots, so they often become armored and provide only a limited source of PM10 during high winds. For these surfaces in a disturbed condition, average PM10 emissions measured from a small wind tunnel agreed well with the measured loose PM10 in the volume of erodible soil that one would need to remove to armor the surface (Hagen and James, 1998). A challenging research problem involving surfaces that become armored is to determine how quickly the PM10 and other erodible aggregates are replenished so these surface soils are again erodible.

In contrast, the PM10 source generally is not limited on large, bare, erodible areas. Emission of loose material may dominate the erosion process on large fields with a dust mulch that consists mainly of suspension-size aggregates. On other surfaces such as large, aggregated fields (Hagen et al., 1996) or crusted, dry lakebeds (Gillette et al., 1997), the abrasion and breakage processes generally dominate the generation of PM10. For hard, armored surfaces such as paved areas or desert pavement, breakage is also likely the dominant PM10 generation process when eroding soils pass. Tests on four Kansas soils showed that PM10 in the portion of the suspension component from abrasion of immobile clods ($SF10_{an}$) ranged from 0.3% to 1.1%. The PM10 in the suspension component from breakage ($SF10_{bk}$) of saltation-size aggregates was larger and ranged from 1.1% to 3.6%.

Data reported by Chandler et al. (2002) also illustrate the importance of breakage in creation of PM10. They used an airstream to rotate individual soil samples around the inside perimeter of an inverted cone during 1 h tests. During a test, the loose PM10 as well as the PM10 broken from both suspension-size and larger aggregates were continually captured in a sampler. Potential PM10 from Columbia Plateau soils measured by this test ranged from 1.5% to 4.1% and averaged 2.8%. In contrast, the resuspension tests of loose PM10 from the same soils averaged 0.64%. Thus, one can infer that roughly 77% of PM10 measured in the cone tests was created by breakage.

Their response to impacts suggests that mobile saltation/creep aggregates possess stronger interparticle bonds than the immobile clods (Mirzamostafa et al., 1998); therefore, their breakage should produce the finest particle size distribution (Ning et al., 1997). The experimental measurements of PM2.5/PM10 ratios generally reflect this trend. For example, resuspension of California soils from a fluidized bed with low breakage yielded ratios of 0.08 to 0.12 (Ashbaugh et al., 2003). In another dust generator, soils from the South Aral Sea Basin were repeatedly dropped from one end to the opposite end of a capped pipe, causing moderate breakage, while the suspended dust was sampled (Singer et al., 2002). Ratios in this test ranged from 0.20 to 0.48. Ratios of PM2.5/PM10 for Columbia Plateau soils circulated in an inverted cone for 1 h ranged from 0.29 to 0.54 (Chandler et al., 2002). However, ratios from resuspension of these same Columbia Plateau soils were even higher than the cone test. The latter result in an unexplained anomaly in the data trend.

In summary, the suspended soil leaving a field can be generated by one or more of three processes. Each process appears to provide significantly different fractions of PM10 and PM2.5 in the suspended soil created by the process. To improve accuracy in modeling PM10, we are investigating the causes for variation in PM10 generation by the individual processes. The objectives of this laboratory study were to determine relative breakage fractions as well as the PM10 and PM2.5 fractions created by simulated erosion impacts of saltation-size aggregates for a range of soils in several western states.

Methods

Soil samples from the upper 1 cm layer were collected from various locations in nine western states: Arizona, New Mexico, California, Nevada, Texas, Oklahoma, Colorado, Kansas, and Nebraska. The samples were air-dried in a laboratory greenhouse and then analyzed. Using a subsample from each soil, the dispersed particle-size distribution was measured by sieving the sand fractions and pipetting the clay fraction, according to the method of Gee and Bauder (1986).

Calcium carbonate and organic matter of subsamples were determined by the Kansas State University Soil Testing Laboratory using standard procedures.

To simulate the breakage of saltation-size aggregates, tests were conducted using the chamber apparatus illustrated in figure 1. Subsamples of the saltation-size aggregates (150 to 840 μm) were gently sieved from the test soils and then impacted on a steel target plate at a velocity of 5.5 m s^{-1} in the test chamber using a calibrated sandblast nozzle. The aggregates were irregular in shape, and preliminary tests showed the coefficient of restitution of aggregate rebounds from a plate were similar to those from strong, immobile soil crusts.

The coarse particles created by impacts were aerodynamically separated by a large cyclone, and fine particles greater than PM10 diameter were impacted on a preseparator plate in a Hi-Vol sampler (model 1200, Anderson-Graseby, Atlanta, Ga.). To obtain the size distribution of the PM10 fraction, the preseparator was followed by a four-stage Hi-Vol cascade impactor (Anderson four-stage cascade impactor, aerodynamic cut diameters of 7.0, 3.3, 2.0, and 1.1 μm, Anderson-Graseby, Atlanta, Ga.) and a back-up

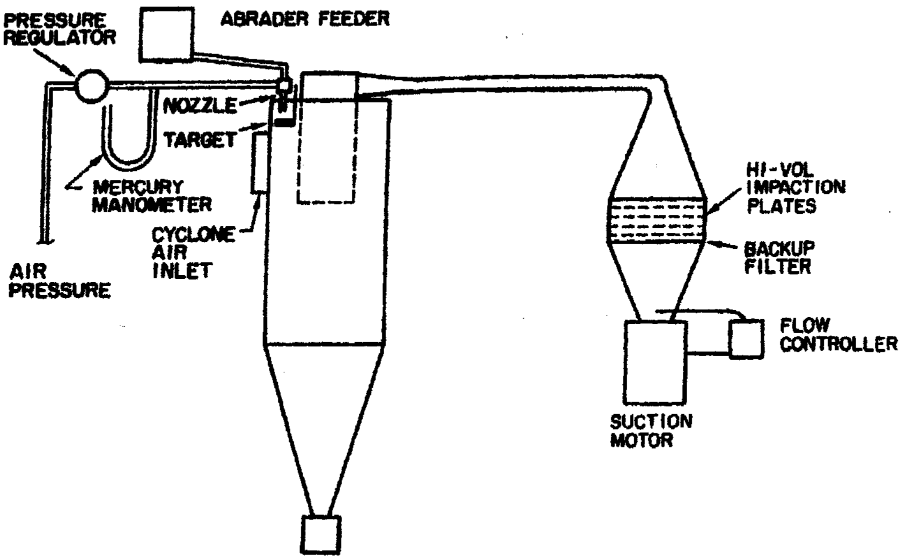

Figure. 1. Schematic diagram of test chamber illustrating sandblast nozzle inside large cyclone with PM10 and PM2.5 sampling on impaction plates located downstream.

filter. A feedback flow-controller maintained the flow at a constant flow rate of 9.4 L s^{-1} (20 CFM).

The PM10 created by the impacts was measured by weighing the filters on the impaction plates. The PM2.5 was calculated from the cumulative size distribution on the filters. The cyclone walls and piping were repeatedly tapped before stopping each run to remove remaining particles. A mass balance of the aggregates input into the sampling train for each run was calculated to provide quality control of the test procedures.

After impacting the sample, the suspension-size (<100 μm diameter) aggregates in the large cyclone were separated by sieving, and the remaining saltation-size aggregates were again impacted. This sieving operation was used to simulate the sorting and removal of the suspension component that occurs during wind erosion. Each sample was subjected to either 4 or 8 consecutive impacts. Average relative breakage fraction per impact for each of the samples was measured as the ratio of the suspension-size soil mass created to the mass of soil impacted.

The soil samples available for testing were small (<10 kg) but were of sufficient size to use in the test chamber. However, the disadvantage of this test procedure is that only relative values for the breakage fraction, and not the absolute coefficient of breakage, could be obtained. However, an absolute coefficient of breakage can be obtained by recycling large soil samples in the wind tunnel to estimate breakage fraction per unit of horizontal travel of the saltation discharge (Mirzamostafa et al., 1998). Future research is planned to relate the relative breakage fractions to the absolute breakage coefficients of reference soils.

Average annual precipitation at the sampling sites ranged from 102 to 787 mm (van der Leeden and Troise, 1974). These data were used along with the dispersed soil particle data as independent variables in regression analyses to explain the variance in the breakage fractions, and in the fractions of PM10 and PM2.5 created by breakage. The regression equations were developed using TableCurve software (SPSS, 1997). The independent variables were added to each equation based on their ability to maximize the coefficients of determination (R^2).

Results and Discussion

Relative breakage per impact provides insight into the rate that various soil aggregates break down to supply suspension-size aggregates (<100 μm diameter) to the atmospheric dust load. The relative breakage per impact from saltation size to suspension size varied among the soils and increased with the soil silt content (fig. 2). However, more of the variance in relative breakage among samples could be explained by the partial regression relating it to the saltation-size sand/clay ratio of the soil sample (fig. 3). When saltation-size sand (>100 μm diameter) content is large, the amount of material available in the aggregate for breakage to <100 μm is limited. In contrast, at low sand and high clay contents, binding forces among the particles reduced the breakage fraction. The average relative breakage fraction was 0.044 in aggregates with saltation-size sand/clay ratios between 0.1 and 10, while in the remaining test soils the average was 0.015. A t-test showed these means were significantly different ($p < 0.01$).

By combining the influence of both soil texture and calcium carbonate, 62% of the variance in the relative breakage fractions could be explained by the following equation ($p < 0.01$) (fig. 4):

$$bk_r = 0.0149 - 0.015\ln(sc) - \frac{0.0044}{sc} + 0.0966 fs^{0.5} - 0.186 cc^2 \ln(cc) \tag{1}$$

where

bk_r = relative breakage per impact (kg/kg)
sc = saltation-size sand/clay ratio (clay fraction 0.017 to 0.43)
fs = fine sand (0.05 to 0.10 mm) (fraction 0.03 to 0.35)
cc = calcium carbonate (fraction 0.01 to 0.33).

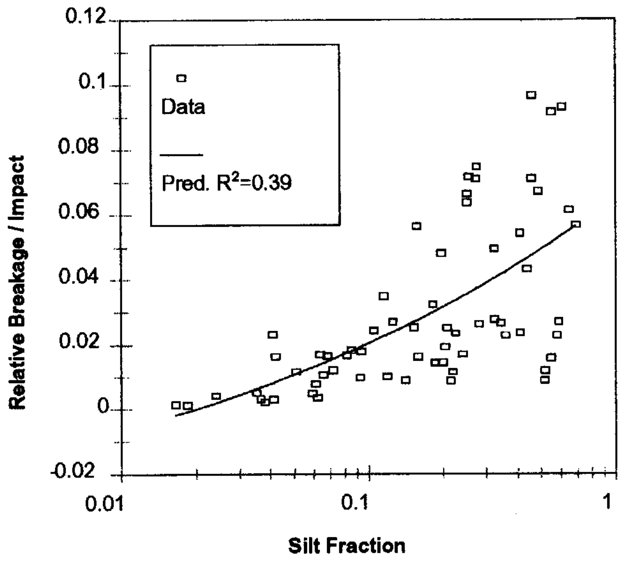

Figure 2. Relative breakage fraction as a function of soil silt fraction.

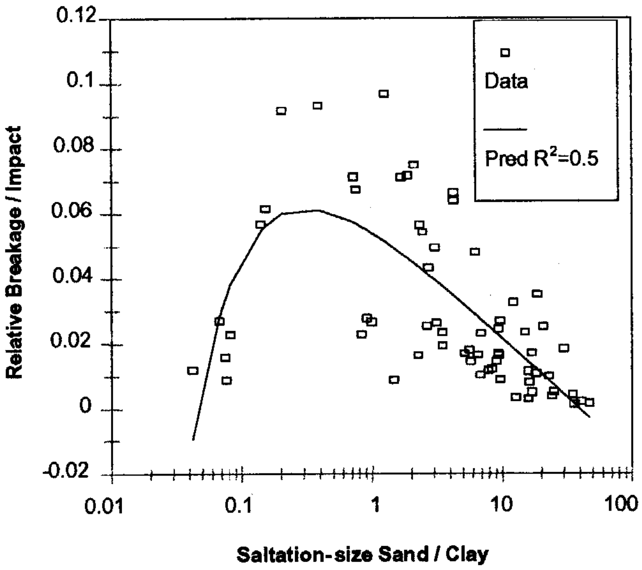

Figure 3. Relative breakage fraction as a function of saltation-size sand/clay along with partial regression prediction equation.

In this study, relative breakage fractions increased with calcium carbonate content, but organic matter had little effect. Other research has shown that PM10 concentration measured from falling soil aggregates in a rotating drum apparatus was positively correlated with both calcium carbonate and organic matter (Zobeck et al., 1999).

As aggregates decrease in size, their breakage fraction decreases. This is likely caused by fewer flaws, because the porosity decreases with aggregate size (Currie, 1966). The breakage fraction per impact also decreases as the number of impacts increases for aggregates that contain a saltation-size sand grain (Mirzamostafa et al., 1998). However, wind tunnel tracer studies show that individual saltating aggregates are frequently buried under ripples or simply replaced by other aggregates, so horizontal progress of individual aggregates is relatively slow (Willets and Rice, 1985). In addition, the saltation-size mass depleted by breakage to suspension size

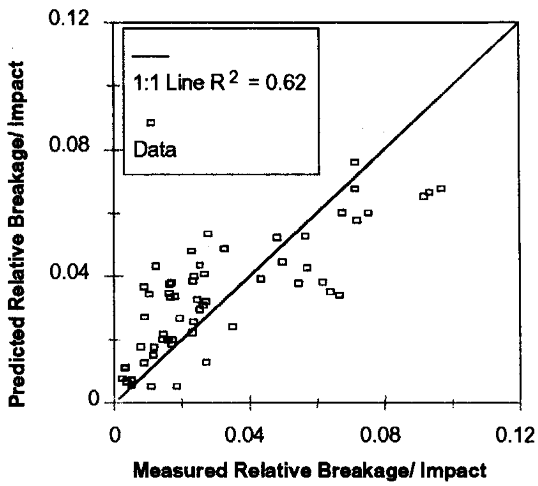

Figure 4. Predicted (eq. 1) breakage fraction compared to measured breakage fraction using saltation-size sand/clay, fine sand, and calcium carbonate as independent variables.

also must be replaced by new aggregates. Thus, on eroding fields, the horizontal discharge of impacting aggregates at any downwind location may be composed mainly of aggregates that have traveled a short distance. However, additional field tracer studies are needed to quantify the mean travel rates for a range of wind and surface conditions.

Because PM10 is regulated as a health hazard, the fraction of PM10 ($SF10_{bk}$) in the suspension-size (<100 μm diameter) soil aggregates created by the breakage impacts is of primary interest. By combining the effects of annual precipitation and clay content as independent variables, 52% of the variance in $SF10_{bk}$ among soils could be explained by the following equation ($p < 0.01$) (figs. 5 and 6):

$$SF10bk = -0.201 - 0.52\ln(c) - 0.422[\ln(c)]^2 - 0.139[\ln(c)]^3 - 0.0156[\ln(c)]^4 + 0.131\left[\exp\left(-\frac{w}{175.6}\right)\right] \quad (2)$$

where

c = clay fraction in soil (range 0.017 to 0.42)

w = annual precipitation (range 100 to 800 mm).

The $SF10_{bk}$ averaged over all soils was 0.049. However, $SF10_{bk}$ was related to the soil clay content (fig. 5), and in a few soils, $SF10_{bk}$ exceeded 0.10 when the clay fraction was less than 0.1. Mean values for $SF10_{bk}$ were 0.069 (clay fraction <0.1) and 0.030 (clay fraction >0.1). A t-test showed that these means were significantly different ($p = 0.01$). Neither the soil organic matter (fractions 0.001 to 0.063) nor calcium carbonate had significant effects on $SF10_{bk}$. Chandler et al. (2002) also found organic matter had little effect.

The mechanisms that generate fine particles from breakage of aggregates are complex. Most are created during impact as a result of semibrittle failure (Ghadiri, 1997; Hagen, 1984). Aggregate breakage generated in computer simulations shows that most of the fine particles are created directly under the aggregate impact zone and from the opposite side of impact zone (Kafui and Thornton, 1993).

As a health hazard, PM2.5 content is also of interest (U.S. EPA, 1996). The average PM2.5/PM10 ratio created by

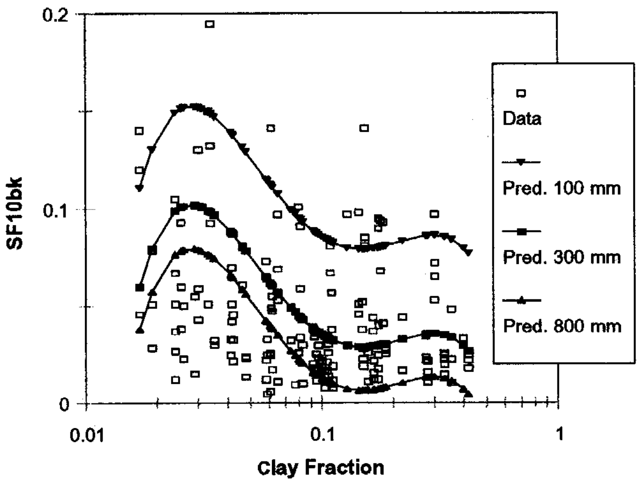

Figure 5. The fraction of PM10 ($SF10_{bk}$) from breakage in the suspension-size aggregates (<100 μm diameter) as a function of soil clay fraction with predicted values of $SF10_{bk}$ (eq. 2) for three levels of annual precipitation.

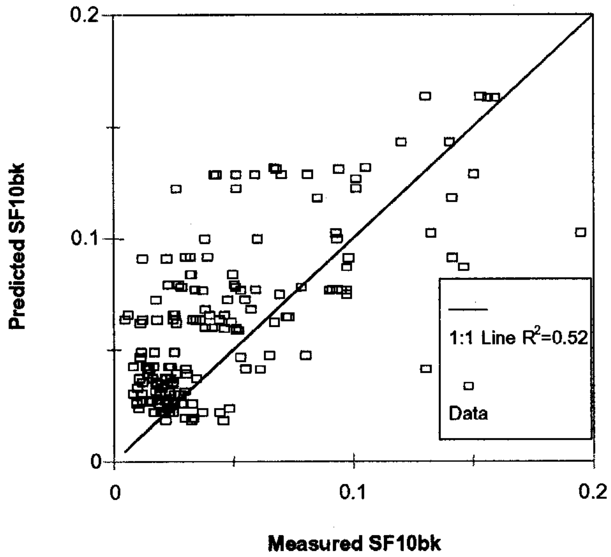

Figure 6. Predicted (eq. 2) versus measured soil fraction of PM10 ($SF10_{bk}$) in suspension-size aggregates (<100 μm diameter) using both clay fraction and annual precipitation as independent variables.

breakage was 0.154. The mean ratio tended to increase linearly with the saltation-size sand/clay ratio from about 0.1 to 0.3 (fig. 7). As precipitation increased, the ratio tended to decrease, and 53% of the variance in the PM2.5/PM10 ratio could be explained by the following estimating equation ($p < 0.01$) (fig. 8):

$$\text{PM2.5/PM10} = 0.1055 + 0.0046sc + 9615.5\left[\exp\left(-\frac{w}{8.72}\right)\right] \quad (3)$$

where

sc = saltation-size sand/clay ratio (clay range 1.7% to 42%)

w = annual precipitation, (range 100 to 800 mm).

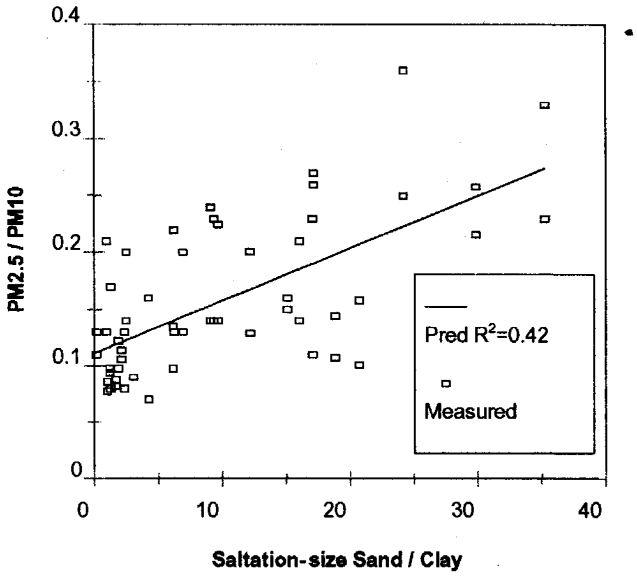

Figure 7. PM2.5/PM10 ratio from breakage as a function of saltation-size sand/clay ratio along with partial regression predicted values.

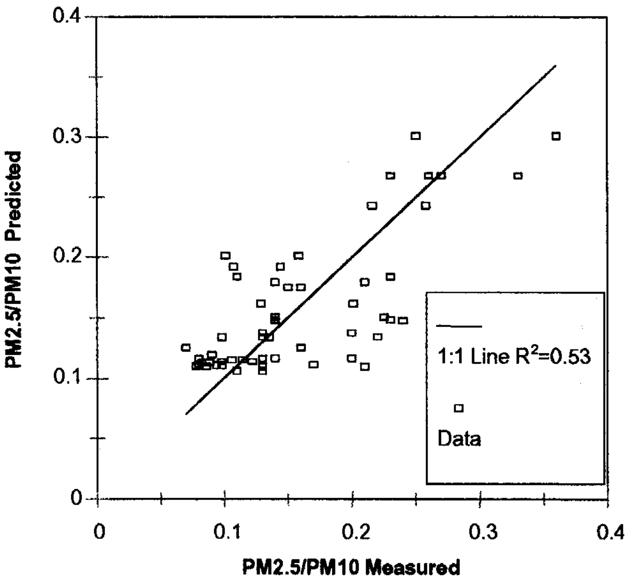

Figure 8. Predicted (eq. 3) versus measured PM2.5/PM10 ratio in suspension-size soil created by breakage as a function of both saltation-size sand/clay and precipitation.

The measured PM2.5/PM10 ratios reported in this study should represent near maximum values that occur among the erosion processes in the test soils, because the impact velocity used was in the upper quartile of expected impact velocities, and the saltation-size aggregates are the strongest aggregates involved in multiple impacts during the erosion processes.

As annual precipitation increased from 100 to 800 mm, the relative breakage by impact decreased and the size distribution of the suspended material became coarser. As a consequence, PM10 and PM2.5 from breakage for a given soil texture tend to increase in regions with low precipitation. Precipitation may serve as an indicator of biological activity that produces "glue" for binding primary particles together. There are additional variables that could be measured to improve the PM10 predictions by breakage. These include effects of temporal soil variability and land management.

Conclusions

Because saltating aggregates impact over a range of velocities, the breakage fractions measured in this study represent only the relative fraction of saltation-size aggregates broken to suspension size (<100 μm diameter) per impact. However, differences were noted among soils and climates. The breakage fraction averaged 0.044 for aggregates with saltation-size sand (>100 μm diameter)/clay ratios between 0.1 and 10. The remaining aggregates with large clay or saltation-size sand contents had significantly ($p < 0.01$) lower breakage fractions that averaged 0.015. The relative breakage fractions were non-linearly related to the saltation-size sand/clay ratio and increased with calcium carbonate content at the sampling locations ($R^2 = 0.62$).

The fraction of PM10 in the suspension component created by breakage ($SF10_{bk}$) averaged 0.049 over all soils. However, the averages were significantly different ($p < 0.01$) depending upon clay content. Average $SF10_{bk}$ was 0.069 for clay fraction <0.1 and 0.030 for clay faction >0.1. The $SF10_{bk}$ was non-linearly related to the soil clay fraction and inversely proportional to annual precipitation ($R^2 = 0.52$).

The measured PM2.5/PM10 ratios from breakage averaged 0.154. These ratios were related to both saltation-size sand/clay ratio and precipitation, and predicted values ranged from about 0.1 to 0.3 ($R^2 = 0.53$). Because of the test conditions, these ratios should represent near-maximum values for the erosion processes in the tested soils. The measured PM2.5/PM10 ratios were generally below 0.3, except for two soils slightly exceeding 0.3. Therefore, the proposed new PM2.5 air quality standard should not be more difficult to attain than the PM10 standard, when local wind erosion is the only major source of PM2.5 affecting the target population.

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