

Particle size fractionation of soil containing coal and combusted particles

M. W. I. SCHMIDT^a, C. RUMPEL^b & I. KÖGEL-KNABNER^a

^aLehrstuhl für Bodenkunde, Technische Universität München, 85350 Freising-Weihenstephan, and ^bDepartment of Soil Protection and Recultivation, Brandenburgische Technische Universität Cottbus, 03013 Cottbus, Germany

Summary

Standard procedure for dispersing natural soils for particle size fractionation can be too aggressive for soil containing coal and other organic particles from coal industries. We have investigated ultrasonic dispersion for the latter in four soils differing in pedogenesis (Phaeozem, Podzol, reclaimed mine soils), carbon content (27.5–138.6 g kg⁻¹), clay content (80–153 g kg⁻¹) and sources of particles (airborne coal dust, combustion residues, lignite particles). As we found previously for natural soils, the ultrasonic energy needed for complete dispersion varies between 450 and 500 J ml⁻¹, but the resulting particle size distributions differ from those obtained by standard textural analysis. This is probably related to the different properties of native soil organic matter and coal and combusted particles. Coal and soot particles may partly resist oxidation with hydrogen peroxide, depending on material and particle size. The diameter of lignite particles, remaining after oxidation, is overestimated in sedimentation analysis by a factor of 1.66. Sand-sized lignite particles can be disrupted by ultrasonication and redistributed to finer particle size fractions. The ultrasonic dispersion and particle size fractionation procedure can be applied to soils containing coal and combusted particles, but caution is needed in interpreting the results if they contain large proportions of coal particles.

Introduction

Physical fractionation has proved useful for studying chemical structure of soil organic matter and following the dynamics. Christensen (1996, pp. 97–165) has recently reviewed the subject, as he had earlier done for methods for dispersion and fractionation of organomineral complexes (Christensen, 1992). More recently we have evaluated systematically ultrasonic dispersion and particle size fractionation to obtain primary organomineral complexes (Schmidt *et al.*, 1999). The energy necessary for complete dispersion of soil aggregates in five soils varying in pedogenesis and physical and chemical properties was determined to be 450–500 J ml⁻¹. The particle size distributions determined in this way were similar to those obtained by the standard method, and a redistribution of organic matter between size fractions or a cleavage of organic macromolecules (Schmidt *et al.*, 1997) could not be detected.

Recently soils containing appreciable amounts of coal and combusted particles were studied in bulk soils (Lichtfouse *et al.*, 1997), and in particle size fractions obtained after ultrasonic dispersion (Schmidt *et al.*, 1996; Rumpel *et al.*, 1998). The behaviour of coal and combusted particles during

pretreatment and dispersion procedures applied in standard texture analysis is poorly understood. Standard texture analysis includes a pretreatment with hydrogen peroxide (H₂O₂) to oxidize organic matter (Gee & Bauder, 1986). For organic matter from industrial processes, the chemical reactivity with H₂O₂ can be slight for soot particles (Wik & Renberg, 1987), and variable for coal particles, depending on particle size and coal rank (van Krevelen, 1993). These apparent differences in chemical reactivity between native soil organic matter and coal particles and combustion residues probably affect the measured particle size distribution, but they have not been investigated. Determinations based on sedimentation ignore particle shape and rely on uniform density for all particles for calculating the equivalent spherical particle diameter. In natural soils most organic matter is removed by pretreatment with H₂O₂. Thus the particle density of quartz can be applied to the remaining particles to calculate the settling velocity. Organic particles from coal industries, however, may resist pretreatment with H₂O₂ and subsequently may be subjected to sedimentation analysis. The effect of a smaller density of coal particles on the yields of sedimentation analysis has not yet been evaluated.

We have evaluated the ultrasonic dispersion and particle size fractionation on four soils differing in pH, texture and carbon content, two containing coal particles and combustion

Correspondence: M. W. I. Schmidt, Max-Planck-Institut für Biogeochemie, 07745 Jena, Germany. E-mail: michael.schmidt@bgc-jena.mpg.de
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residues deposited from the air and two reclaimed mine soils comprising a mixture of Tertiary sediments and lignite, ashes and organic matter formed after afforestation. Our objectives were (i) to determine the ultrasonic energy necessary for complete dispersion of these soils, (ii) to calibrate the resulting particle size distribution against those obtained by standard analysis, and (iii) to explore the chemical reactivity of coal and combusted particles with H_2O_2 and the behaviour of these particles in sedimentation analysis.

Materials and methods

Soils and other organic materials

The soils containing organic particles from coal industries originate from highly industrialized areas in Germany. In the Aeh horizon of a Haplic Podzol (FAO, 1994) under forest in the northern Ruhr area, large amounts of airborne coke and char particles accumulated for decades. The Axp horizon of a Haplic Phaeozem originates from agricultural land near a briquette factory south of Halle/Saale and contains large amounts of coal dust (Schmidt *et al.*, 1996). The reclaimed mine soils in Lausatia were ameliorated with ash from coal combustion and forested about 30 years ago. At one site (Mine Soil 1) the parent material is rich in lignite, the other (Mine Soil 2) contains little lignite (Rumpel *et al.*, 1998). Soils were classified according to FAO guidelines (FAO, 1994), and horizons were designated according to the German Soil Survey Description (AG-Boden, 1994). Table 1 lists relevant soil properties. As a reference, the Axp horizon of a natural Haplic Phaeozem was sampled from an agricultural plot north of Halle/Saale (Schmidt *et al.*, 1996), and the data for this soil are listed also.

Because particles from coal industries contribute to the soil organic matter (SOM), the tentative source materials themselves were sampled. Lignite briquettes (organic carbon 554.4 g kg^{-1}) and furnace ash were taken from the briquette factory mentioned above. Bituminous coal was sampled from an outcrop of a carboniferous coal seam in the southern Ruhr area. Furnace soot from coal combustion came from a house heating system fuelled by local bituminous coal. Charcoal, elemental carbon (Roth GmbH, Germany) and furnace soot (N326, Degussa, Germany) were obtained commercially.

Sample pretreatment, chemical analysis and microscopy

Roots and visible plant remains were mechanically removed from the samples. Except for the samples from the mine soils, which were air-dried, samples were freeze-dried. Soil aggregates were crushed, and the fraction $>2 \text{ mm}$ was removed by dry sieving. For chemical analysis an aliquot was ground in a ball mill for 10 min. The pH was measured with a glass electrode in the supernatant of a 2.5:1 (by weight) water:soil suspension. The contents of carbon (C) and nitrogen

(N) were determined in duplicate with an Elementar Vario EL by dry combustion (minimum detection level for C and N $0.1 \pm 0.3 \text{ g kg}^{-1}$). Dissolved organic carbon was determined with a Shimadzu TOC Analyser. We counted microscopic particles under a light microscope equipped with a point-counting grid at a magnification of 100 times. For each sample approximately 250 counts were used and normalized to 100%. Lignite and bituminous coal were crushed with mortar and pestle to a particle size of $<2 \text{ mm}$. A subsample of the bituminous coal was ground in a ball mill for 10 min.

Chemical degradation by hydrogen peroxide

Mass loss on chemical degradation of organic matter by hydrogen peroxide was measured for the natural reference soil, the soils comprising coal particles and possible contaminants. The samples were chemically degraded using the standard particle size fractionation procedure (Gee & Bauder, 1986). Briefly, 20 g of sample was treated with H_2O_2 (10%) initially at room temperature. After gas development ceased to evolve, suspensions were boiled for 24 h, respectively, 72 h total treatment time, and eventually dried at 105°C . The resulting decrease in mass was determined gravimetrically.

Calibration of the power output

Samples were dispersed ultrasonically with a Labsonic U (Braun Melsungen, Germany) equipped with a titanium probe (19 mm diameter). The cavitation energy applied by ultrasonication was measured calorimetrically with demineralized water (North, 1976). Schmidt *et al.* (1999) describe the analytical details.

Dispersion techniques

We used three procedures for dispersing the soil.

1 According to the standard particle size fractionation (Gee & Bauder, 1986) samples were treated with H_2O_2 (10%). After frothing ceased, samples were heated for a maximum of 24 h total treatment time. Subsequently 0.5 l of demineralized water and 0.4 M sodium polyphosphate were added and the suspension was shaken horizontally overnight.

2 Samples were dispersed by shaking 30 g soil in 150 ml demineralized water on a horizontal shaker for 30 min.

3 For ultrasonic dispersion a soil suspension (30 g soil in 150 ml water) was prepared in a 250 ml glass beaker (diameter 70 mm, height 130 mm) and allowed to stand for at least 3 h. The probe tip of the ultrasonic device was immersed 15 mm into the suspension. The temperature of the suspension was kept below 35°C using a water cooling jacket. The ultrasonifier was operated at a constant power calorimetrically determined at 75 W. Treatment times between 1 and 20 min produced a range of energies between 30 and 590 J ml^{-1} . Between treatments the instrument was allowed to cool for 15 min.

Table 1 Physical and chemical characteristics of the investigated soils

Soil class ^a and horizon ^b	Depth /cm	pH (H ₂ O)	Organic C /g kg ⁻¹	Total N /g kg ⁻¹	C:N	DOC ^c /% of total soil C	Particle size ^d (limits in μm) /g kg ⁻¹							
							2000–630	630–200	200–63	63–20	20–6	6–2	2–0.45	
Natural soil:														
Haplic Phaeozem Axp	0–20	6.5	22.6	2.0	11	1.0	20	106	184	288	160	51	193	
Soils containing coal and combusted particles:														
Haplic Podzol Aeh	0–8	3.6	102.0	3.8	27	0.7	29	518	157	119	70	26	80	
Haplic Phaeozem Axp1	0–25	6.2	138.6	3.6	39	0.7	3	23	55	384	303	107	127	
Mine Soil 1 IyC	20–50	6.0	58.5	1.1	53	–	51	279	381	51	54	29	153	
Mine Soil 2 Ah	0–2	6.0	27.5	0.9	31	–	93	357	328	34	35	22	129	

–, Not determined.

^aClassification according to FAO (1994).^bHorizon designation according to AG-Boden (1994).^cDissolved organic carbon in the soil suspension. After dispersion with 440 J ml⁻¹ the content of dissolved organic carbon was determined for the fraction <0.45 μm with an aliquot of the solution and from these data the percentage of total organic C was calculated.^dResults obtained by standard particle size analysis as described in Materials and methods.

The energy dissipation into the suspension E (J ml^{-1}) was calculated by the equation $E = P t V^{-1}$, where P is the power output (W), t is the sonication time (s) and V is the volume of the suspension (ml). The volume of the soil suspension is calculated using an average particle density of 2.6 g cm^{-3} and water density of 1.0 g cm^{-3} .

Particle size fractionation

The dispersed samples were fractionated into three sand fractions ($630\text{--}2000 \mu\text{m}$, $200\text{--}630 \mu\text{m}$, $63\text{--}200 \mu\text{m}$), a coarse silt ($20\text{--}63 \mu\text{m}$) and a medium silt fraction ($6\text{--}20 \mu\text{m}$). The mine soils contained little clay, and so clay and fine silt size particles were collected in one fraction $<6 \mu\text{m}$. The soils were fractionated in sedimentation cylinders following the standard pipette and sieve method (Gee & Bauder, 1986). Samples were transferred into sedimentation cylinders, topped to 1.0l, shaken end over end and then allowed to settle. Settling times for 2, 6, 20 and $63 \mu\text{m}$ particles for temperatures between 18 and 28°C were calculated for the particle density of quartz (2.65 g cm^{-3}) according to Stokes's law (Table 3). Water temperature was measured in an additional sedimentation cylinder. Particle size limits refer to equivalent spherical diameter, signifying the diameter of spherical particles with the same density and settling velocity as the analysed particle. Aliquots of silt and clay fractions were decanted in preweighed beakers, dried at 105°C and weighed again. The remaining fraction was washed over a nest of sieves ($630 \mu\text{m}$, $200 \mu\text{m}$, $63 \mu\text{m}$), dried at 60°C and the mass determined gravimetrically. The standard deviations for the ultrasonic dispersion-particle size fractionation were previously determined for 12 samples from natural soils (Schmidt *et al.*, 1999), and varied for individual fractions between 1 and 6 g kg^{-1} of soil. Here we measured additionally three replicates of the Podzol Aeh horizon and pooled both data sets, resulting in $n=15$ soil samples each including seven size fractions. From this pooled data set we could calculate the average variances ($s^2=1\text{--}7 \text{ g}^2 \text{ kg}^{-2}$), the pooled standard deviations from the averaged variances ($\text{SD}=0\text{--}6 \text{ g kg}^{-1}$), and the pooled standard errors of the averaged variances ($1\text{--}2 \text{ g kg}^{-1}$).

Results and discussion

Determination of ultrasonic energy for complete dispersion

First, the influence of increasing ultrasonic dispersion energy on the yields of the different particle size fractions was investigated to ensure that dispersion was complete. Second, the particle size distribution after complete dispersion was calibrated against standard textural analysis. Data are given as g fraction per kg whole soil.

Complete dispersion. Yields of the sand fractions were larger after dispersion by shaking with water (Figure 1). They

decreased consistently with increasing input of ultrasonic energy (between 30 and 590 J ml^{-1} : -50 to -120 g kg^{-1}), and reached a plateau between 450 and 500 J ml^{-1} of applied energy. A similar decrease can be observed for the coarse silt fractions (-20 to -30 g kg^{-1}), whereas yields of the medium and fine silt+clay fractions increase ($+50$ to $+120 \text{ g kg}^{-1}$) accordingly. The exception, Mine Soil 1, will be discussed below. With increasing dispersion energy sand yields decrease, while fine silt+clay yields increase. This demonstrates with small amounts of ultrasonic dispersion energy that sand size fractions include aggregates composed of smaller primary organomineral complexes. With increasing dispersion these aggregates disintegrate into smaller aggregates and primary organomineral complexes, resulting in a continuous accumulation of fine silt+clay-sized organomineral complexes. Changes in yields level off between 450 and 500 J ml^{-1} , suggesting that with more energy there is no additional breakdown of aggregates, and only primary organomineral complexes are left in these fractions.

Changes in yields are greater in these soil samples (maximum difference $\pm 120 \text{ g kg}^{-1}$) than the natural ones we studied earlier (maximum difference $\pm 30 \text{ g kg}^{-1}$) (Schmidt *et al.*, 1999). This suggests that coal and combusted particles are less resistant to ultrasonication than natural soils. This is especially evident in Mine Soil 1, which contains a large proportion of lignite particles. The fragility of the particles in this soil becomes even more obvious when the yields obtained after shaking with water (displayed at zero power) are considered. Loss in the sand fraction (-170 g kg^{-1}) and gain in the fine silt+clay fraction ($+160 \text{ g kg}^{-1}$) are larger than those in other soils. By contrast, the yields of the medium silt fraction decrease with increasing ultrasonic energy, and shaking seems to disperse the soil more effectively than ultrasonication with 30 J ml^{-1} . To some degree these results may be explained by the small-scale spatial heterogeneity of the substrate, which is typical for reclaimed mine soils. But this pattern of disintegration may be related also to the previous observation that mine soils containing lignite particles are less resistant to ultrasonic dispersion than natural soils.

Our microscopic studies of this soil revealed that lignite particles in the coarse sand fraction were less stable after ultrasonic dispersion (Figure 2). After limited dispersion by shaking with water, lignite particles contribute the majority (40%) of the visible particles, whereas quartz grains, soil aggregates and fly ash are less important. With increasing dispersion ($100\text{--}200 \text{ J ml}^{-1}$) the proportion of visible coal particles and soil aggregates decreases rapidly, leaving only quartz and fly ash particles. Obviously, lignite particles can be disrupted by relatively little ultrasonic energy and redistributed to smaller size fractions, whereas for natural soils the redistribution of organic matter towards smaller size fractions seems to be less important. Structural alterations caused by high energy ultrasonic dispersion were not evident for organic

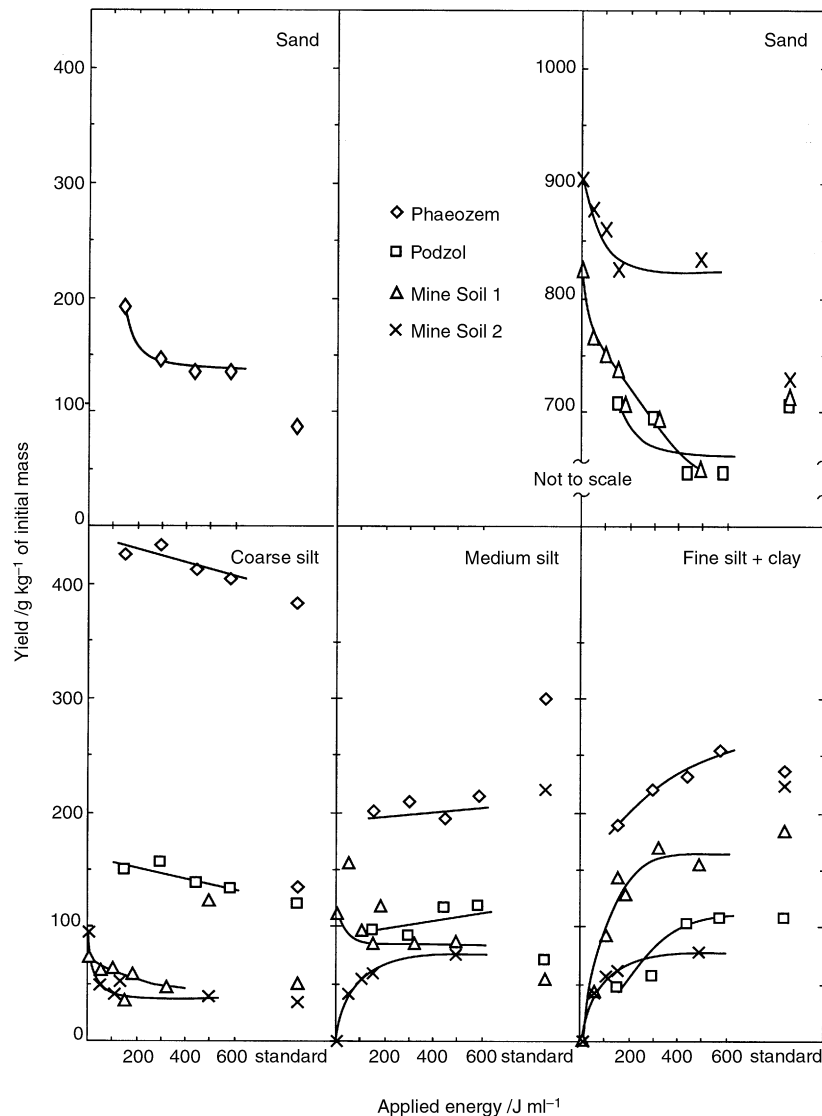


Figure 1 Influence of ultrasonic dispersion energy on yields of particle size fractions compared with standard texture analysis. Yields of particle size fractions after shaking in water and ultrasonic dispersion ($30\text{--}590\text{ J ml}^{-1}$) were connected by curves drawn by hand, and results from standard texture analysis were displayed as 'standard'. For better comparison all ordinates are adjusted to cover a range of 450 g kg^{-1} . Owing to large differences in sand content, data for the sandy soils (Podzol and Mine Soils 1 and 2) are displayed in a separate graph, where the origin of the ordinate is not to scale. For the ultrasonic dispersion and particle size fractionation procedure the pooled standard errors of the averaged variances varied between 1 and 2 g kg^{-1} ($n=15$). Details are given in the Materials and methods section.

matter in the presence of quartz sand and soil material (Schmidt *et al.*, 1997), minerals in the presence of SOM (Watson, 1971) and the surface area of clays (Gregorich *et al.*, 1988).

Calibration to standard textural analysis. In the following, the particle size distributions resulting from ultrasonication with $450\text{--}500\text{ J ml}^{-1}$ are calibrated against those obtained by standard particle size analysis (included in Figure 1). For natural soils, ultrasonic dispersion with $450\text{--}500\text{ J ml}^{-1}$ was found to result in (i) complete dispersion and (ii) particle size

distributions that correspond well with those obtained from standard analysis (Amelung *et al.*, 1998; Schmidt *et al.*, 1999). For the soils studied here, particle size distributions obtained after ultrasonic dispersion were different from those after standard analysis. For the Phaeozem and Mine Soil 2, sand yields were larger ($+70$ and $+90\text{ g kg}^{-1}$, respectively) and medium silt yields were much less (-100 g kg^{-1} and -150 g kg^{-1} , respectively) than the amounts determined with standard methods. The Podzol and Mine Soil 1 showed opposite trends for sand yields (-40 to -50 g kg^{-1}) and medium silt yields ($+30$ to $+40\text{ g kg}^{-1}$). These controversial patterns for

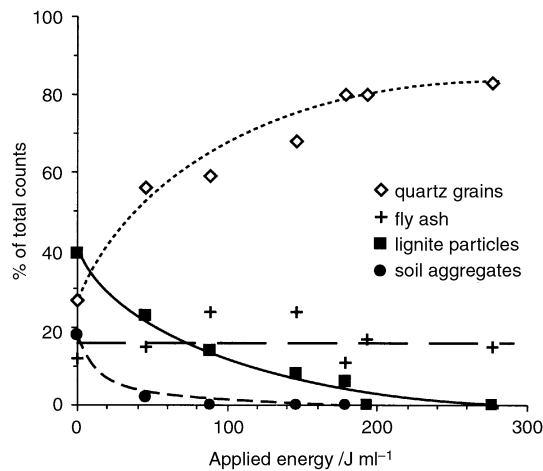


Figure 2 Influence of ultrasonic energy on particles in the coarse sand fraction of Mine Soil 1 as revealed by microscopy.

the two groups did not occur with the fractions coarse silt and fine silt+clay, where yields were similar to standard analysis, except for Mine Soil 1 (-140 g kg^{-1}).

As a result, there are apparent differences in particle size distributions between results obtained after ultrasonic dispersion and those determined by standard analysis. These differences could be related to the greater resistance of coal and combusted particles to oxidation by hydrogen peroxide and the smaller density of these particles, and they are discussed below.

Resistance of coal and combusted particles to oxidation by H_2O_2

The extent of degradation of organic matter from natural soils and soils containing organic particles from coal industries by hydrogen peroxide (H_2O_2 , 10%) can be assessed by comparing the mass of the sample before and after oxidation (Table 2). Treating the natural soil (Haplic Phaeozem Axp) with H_2O_2 for 24 h caused it to lose 4% of its mass. It lost no more mass after 72 h, indicating that oxidation of organic matter did not continue after 24 h, and confirming that the pretreatment applied in standard texture analysis is effective for natural soils. By contrast, the soils containing organic particles from the coal industries lost mass between 24 and 72 h of treatment, indicating that oxidation of organic matter continued for more than 24 h. Also for coal as typical constituent of the soils studied here, more than 24 h of treatment are necessary until visible oxidation with hydrogen peroxide stops. The mass was larger when bituminous coal was milled finely (83%) than when it was crushed (7%), and the decrease in mass was larger for the lignite (74%) than for the bituminous coal (7%) and other material with condensed carbon structures, such as charcoal, elemental carbon, soot and ashes (<1%). These results confirm previous results, summarized by van Krevelen

(1993), and demonstrate the different resistances of natural soil organic matter and coal and combusted particles.

Summarizing, the organic particles originating from coal industries oxidized more slowly than natural soil organic matter, and the extent of oxidation was affected by (i) particle size and (ii) type of material, e.g. degree of condensation of the organic matter. As a result, two facts have to be considered when analysing the particle size distribution of soils containing coal or combusted particles. First, the treatment with H_2O_2 cannot differentiate between natural organic matter and coal particles. Second, coal and combusted organic particles may resist the pretreatment with hydrogen peroxide and subsequently may contribute to the particle size distribution as determined by standard texture analysis.

Behaviour of coal and combusted particles in sedimentation analysis

The effect of different particle densities on the diameters measured by sedimentation was calculated by Stokes's law (Table 3). In standard particle size analysis and in this study, particle shape of the settling particle is ignored and its density (ρ_{particle}) is assumed to be equal to a quartz sphere (2.65 g cm^{-3}). Consequently, less dense particles have a larger diameter than quartz particles with the same settling velocity (Table 3). For organomineral complexes with a particle density of 2.36 g cm^{-3} the real diameter would be larger by a factor of 1.10 compared with the measured diameter, which can be neglected considering the numerous other assumptions underlying sedimentation analysis. By contrast, the measured diameter of a lignite particle, which may be part of the soils studied here, can be larger by a factor of 1.66. As an example, a fine silt-sized lignite particle ($4 \mu\text{m}$) would be recovered with the medium silt fraction ($6.6 \mu\text{m}$). However, due to the widely varying particle densities in the soils investigated, errors resulting from the application a single average particle density cannot be ignored.

Other components of ultrasonified soil suspensions could be particles of organic matter not associated with mineral particles (e.g. detached organic matter). The diameter of these particles would be larger by a factor of 2.87, compared with quartz particles with the same settling velocity. The small density and presumably small particle size would cause these particles to settle slowly and therefore to be recovered with the clay and $<0.45 \mu\text{m}$ fraction, unless they were readily re-adsorbed. However, small proportions of organic carbon in the $<0.45 \mu\text{m}$ fraction ($\leq 1\%$ of the total soil carbon) in the soils investigated (Table 1) suggest that detached organic matter seems to be quantitatively less important in the suspensions of the Phaeozem and the Podzol, confirming results from our earlier studies of natural soils. To reduce a potential redistribution of coal particles further, the coarse particle size fractions can be removed after limited dispersion, and subsequently ultrasonic dispersion can be completed as

Table 2 Decrease in mass on oxidation with hydrogen peroxide (H₂O₂, 10%) for 24 and 72 h for a natural soil, soils comprising organic matter from coal industries and possible source materials

Sample	Decrease in mass /% of initial mass	
	After 24 h	After 72 h
Natural soil:		
Haplic Phaeozem Axp	4	4
Soils comprising coal and combusted particles:		
Haplic Phaeozem Axp1	10	34
Haplic Podzol Aeh	10	12
Mine Soil 1 lyC	3	5
Mine Soil 2 Ah	2	5
Possible source materials:		
Lignite, crushed	17	74
Bituminous coal, crushed	3	7
Bituminous coal, milled	46	83
Charcoal	<1	<1
Elemental carbon	<1	<1
Furnace soot	<1	<1
Furnace ash from lignite combustion	<1	<1
Furnace ash from bituminous coal combustion	<1	<1

suggested for natural soils (Andreux *et al.*, 1980; Balesdent *et al.*, 1991; Amelung *et al.*, 1998).

Conclusions

We evaluated an ultrasonic dispersion and particle size fractionation procedure to isolate primary organomineral complexes from soils consisting of a mixture of native soil organic matter and organic particles from coal industries. As with natural soils, 450–500 J ml⁻¹ calorimetrically determined energy was sufficient to disperse the soil material completely. Microscopy enabled us to detect the redistribution of organic matter between particle size fractions due to ultrasonication of a reclaimed mine soil containing large proportions of lignite particles. If less ultrasonic energy was used, primary lignite particles were preserved, but the organomineral complexes might be incompletely dispersed. In contrast to results from natural soils, the calibration of the particle size distribution after ultrasonic dispersion against standard texture analysis shows striking differences. These considerable differences in particle size distribution may be explained by a combination of three mechanisms, as follows.

1 The resistance of organic particles from coal industries to oxidation by H₂O₂, as applied in standard texture analysis, can differ from that of coal and combusted particles. Depending on

Table 3 Influence of particle density on the measured diameter obtained by sedimentation analyses, calculated from Stokes's law^a

Sample	Density ρ /g cm ⁻³	Diameter D of sample particle with same settling velocity as quartz ^b
Quartz	2.65	1.00
Organomineral complex ^c	2.36	1.10
Lignite	1.60	1.66
Soil organic matter ^d	1.20	2.87

^a Stokes's law is $\nu = [g d^2 (\rho_{\text{particle}} - \rho_{\text{liquid}})] / 18\eta$ where ν is the settling velocity of the particle (m s⁻¹), g is acceleration induced by gravity (m s⁻²), ρ_{particle} is the particle density (g cm⁻³), ρ_{liquid} is the density and η (Mg (m s⁻¹)) is the viscosity of the liquid in which sedimentation takes place.

^b $D = \text{diameter}_{\text{sample}} : \text{diameter}_{\text{quartz}} = [(\rho_{\text{liquid}} - \rho_{\text{quartz}}) : (\rho_{\text{liquid}} - \rho_{\text{sample}})]^{1/2}$. ^c Calculated density ρ for an organomineral complex consisting of 20% soil organic matter and 80% quartz.

^d Assumed density after Christensen (1992).

type and particle size, these particles can resist degradation with H₂O₂ to an unknown extent.

2 Ultrasonic dispersion does not degrade natural organic matter, but may disperse coal particles.

3 When these differently pretreated samples are subsequently fractionated by sedimentation analysis, the particle size of coal will be overestimated compared with quartz and organomineral complexes in natural soils, because it is less dense. However, errors resulting from particle heterogeneity (density, physical and chemical stability) in one sample cannot be ignored because sedimentation relies on one average density of the analysed particles.

As a consequence, the ultrasonic dispersion and particle size fractionation procedure allows reproducible separation of primary organomineral complexes from soils containing coal and combusted particles without creating artefacts, although caution is needed if soils contain large proportions of coal particles.

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