

An energy based parameter for the assessment of aggregate bond energy

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SUMMARY

The energy applied to a soil–water suspension by an ultrasonic probe was determined for seven vertisol soils using calorimetric techniques. The rate of energy consumed by aggregate dispersion during sonification was calculated as the difference between the energy components measured before and after complete dispersion. Dispersive energy consumption was found to vary significantly during sonification and significant differences ($P < 0.05$) were found between soils for the total dispersive energy required for complete dispersion. The soil dispersion characteristic curves, which relate the dispersive energy consumption during sonification to the quantity of $< 2 \mu\text{m}$ and $< 20 \mu\text{m}$ material dispersed, were also significantly different between soils. Error analysis of the calorimetric technique revealed that the energy consumed by complete dispersion is calculated with a precision of $\pm 0.5 \text{ J g}^{-1}$. For the soils studied, this was smaller than the observed variance in total dispersive energy consumed suggesting sample variability was the major source of variation.

The ultrasonic technique was also used to determine the equivalent total energy applied and the amount of energy consumed by aggregate breakdown and dispersion during 30 min of end-over-end shaking. No significant difference ($P < 0.05$) was found between soils for the total energy applied. However, a significant difference ($P < 0.05$) was observed between soils for the quantity of dispersive energy required to produce the equivalent end-over-end dispersion.

INTRODUCTION

The susceptibility of soil aggregates to breakdown may have a significant effect on a range of soil physical properties of agronomic importance such as macroporosity, pore size distribution, hydraulic conductivity, compactability and erodibility. Methods of assessing soil structural stability generally involve dilute soil–water suspensions (e.g. end-over-end shaking and wet sieving). These techniques are relatively simple to conduct and results are often correlated to observed soil behaviour (Cook & So, 1987). However, the major limitation to these techniques has been the empirical approach and unquantified nature of the energy applied to the suspensions. Although the resultant particle size distribution may be readily measured, the energy applied to produce this distribution has not been quantified. If the energy applied to the suspension can be characterized, this will provide a convenient basis for the comparison of aggregate breakdown under various conditions.

Workers using rainfall simulators and raindrop tests (Bruce-Okine & Lal, 1975; Farres, 1980; Savat & Poesen, 1981) have identified relationships between the energy of raindrop impact and soil detachability or aggregate breakdown. However, the prohibitive time and cost associated with the conduct of these tests limits their application for routine analysis. Kowal *et al.* (1973) and Imeson *et al.* (1981) measured the impact energy of raindrops using piezo-electric transducers. In these measurements, the voltage pulse produced by the transducer is proportional to the strain produced

by the raindrop impact (Imeson *et al.*, 1981). By vibrating the transducer with an alternating voltage, it is possible to reproduce a similar strain. This is the mode of action utilized by ultrasonic transducers in soil dispersion studies.

North (1976) investigated the application of a quantified level of ultrasonic energy to a soil-water suspension and its effect on the dispersion of aggregates. By accounting for various components of the energy balance, the dispersive energy consumed by the breakdown of these aggregates was determined. However, Koenigs (1978) criticized North's experimental technique and disputed the calculation of dispersive energy as a constant with sonification time. Despite the widespread adoption of ultrasonic techniques for the complete dispersion and particle size analysis of soils (Edwards & Bremner, 1964, 1967; Busacca *et al.*, 1984; Gee & Bauder, 1986), there has been very little research conducted to confirm or extend North's findings.

This paper describes an improved ultrasonic technique for quantifying the total energy applied to a soil-water system, the energy consumed during breakdown and dispersion of the soil aggregates and a comparison with the traditional end-over-end shaking technique.

THEORY

When energy is applied to a soil-water suspension, the energy input should be equal to the sum of the energies absorbed by the various components of the system plus the energy lost from the system. Thus, when energy is dissipated in a soil-water suspension by an ultrasonic probe, the resultant energy balance may be expressed as:

$$E_i = E_h + E_c + E_t + L \quad (1)$$

where E_i = energy input, E_h = energy consumed in heating the system, E_c = energy lost by conduction and in other ways from the system, E_t = energy lost by transmission of wave energy from the system, and L = energy consumed by aggregate breakdown.

The majority of the energy applied to the suspension is converted into heat energy (E_h) which may be calculated from:

$$E_h = (m_w c_w + m_s c_s + W_c) \Delta T \quad (2)$$

where m_w = mass of water, c_w = specific heat of water, m_s = mass of oven-dried soil, c_s = specific heat of the soil, W_c = heat capacity of the container, and ΔT = change in temperature of the system.

As the temperature of the suspension rises, energy will be lost from the system to the surrounding media mainly by conduction (E_c) and may be calculated from the cooling characteristic for the system. The energy lost from the system due to transmission (E_t) is a negligible component in the energy balance due to almost complete internal reflection of the ultrasonic waves (Vigoureaux, 1950). Hence, $E_t \approx 0$ for all cases and L can be calculated if E_i is known.

Calculation of E_i from the power readings of the ultrasonic probe do not provide sufficiently accurate values and an alternative measurement is required. In a soil suspension that is completely dispersed, no energy will be consumed by aggregate breakdown. Hence, $L = 0$ and the energy applied to the system is equal to:

$$E_i = E'_h + E'_c \quad (3)$$

where E'_h = energy consumed in heating (after complete dispersion), and E'_c = energy lost by conduction (after complete dispersion).

If the same total energy (E_i) is applied to both a partially and a completely dispersed suspension, L can be calculated from:

$$L = (E'_h + E'_c) - (E_h + E_c) \quad (4)$$

provided there is no effect of changes in the particle size distribution on the energy dissipated in the system. Preliminary trials to compare the energy dissipated into suspensions with similar amounts of fully dispersed soil (68% clay, 8% silt, 24% sand) and fine washed sand (100% sand) showed no effect of particle size distribution.

Each term in Equation (4) can be expressed as energy per unit time (power), which allows the determination of the power applied to the system and the rate of dispersive energy consumption during sonification as:

$$\frac{L}{\Delta t} = \frac{(E'_h + E'_c)}{\Delta t} - \frac{(E_h + E_c)}{\Delta t} \quad (5)$$

To minimize variations in E_p , the two components on the right of Equation (5) can be derived from a single dispersion procedure. Thus, when the calculated $(E_h + E_c)/\Delta t$ values for each time interval during sonification are subtracted from $(E'_h + E'_c)/\Delta t$, determined after effective dispersion ceased (Fig. 1), the values obtained provide a measure of the rate of dispersive energy consumption during sonification. Note that, in this context, the term dispersive energy includes energy consumed by both aggregate breakdown and clay dispersion. The relationship between the cumulative dispersive energy and the quantity of material released during dispersion is the soil dispersion characteristic curve (SDCC), originally proposed by North (1976).

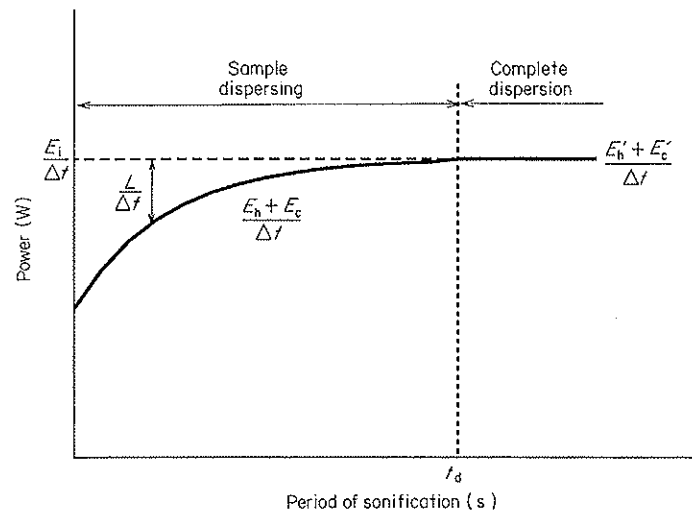


Fig. 1. Idealized energy consumption during sonification of a soil-water suspension.

MATERIALS AND METHODS

Soils

Composite surface samples of seven vertisols (Soil Survey Staff, 1975) from the Darling Downs and Lockyer Valley region of south-eastern Queensland were utilized in this trial. All samples were air dried, crushed to pass through a 2-mm mesh and homogeneously mixed before storage in air-tight containers at constant temperature ($20 \pm 1^\circ\text{C}$) until use.

Exchangeable cations for each soil were determined by the method of Thomas (1982). Carbonate carbon was determined by the method of Allison & Moodie (1965) while organic carbon was determined using the Walkley & Black (1934) method. Particle size distributions were measured using the method of Gee & Bauder (1986). The specific heat capacities of the soils were determined using the summation method described in North (1976).

Experimental technique

All trials were conducted in a constant temperature environment at $20 (\pm 1)^\circ\text{C}$. The air-dry equivalent of 5 g oven-dried soil was immersed in 30 g of degassed, deionised water. Preliminary trials showed that degassing the water prior to sonification resulted in more uniform replication,

presumably because there was less cavitation during sonification. Samples were sonified in cylindrical glass vials with an internal diameter of 23 mm, height 84 mm and approximate wall thickness of 1 mm. During sonification, vials were placed in 1-cm thick polystyrene jackets for insulation. There was no evidence of flocculation in the suspension after sonification and, hence, the addition of a deflocculant was not required.

The ultrasonic instrument used was a probe type Branson Sonifier 250 (Branson Sonic Power, Danbury, CT, USA) operating at 20 000 (± 500) Hz. This instrument has an adjustable power output producing a nominal maximum of 200 W. A reduction module supplied by the manufacturer was fitted between the transducer and horn to reduce the output energy of the ultrasonic probe by approximately 50%. The cylindrical probe has a replaceable tip constructed of titanium alloy with an end surface area of 127 mm². Depth of probe insertion into the suspension was found to affect the energy dissipated into the system by ± 0.11 W mm⁻¹. Hence, insertion was fixed at a depth of 22 ± 1 mm. The instrument was fixed at setting 2 which dissipated 8.9 (± 0.3) W into the soil suspension, measured calorimetrically.

The temperature of the suspension was monitored using a silicon diode sensor encased in a stainless steel protective sheath with an external diameter of 3 mm (resolution ± 0.01 °C, half time for response < 3 s). This sensor was inserted into the suspension to a depth of 30 mm, 15 mm from the centre line of the ultrasonic probe. Temperature changes within the suspension during sonification were recorded by an electronic data logger at intervals of 1 s.

The effect of sonification on aggregate breakdown was determined by measuring the particle size distribution of the soil samples after various periods of sonification up to 900 s. Suspensions were transferred to 250-cm³ glass beakers and made up to 200 cm³ with deionised water equilibrated to the same temperature and mixed homogeneously. After the appropriate settling period, subsamples of 12.8 cm³ were extracted with a pipette to determine the quantity of <2 μ m and <20 μ m equivalent spherical diameter particles.

Dispersion curves for the <2 μ m and <20 μ m material for individual soils were fitted by a least squares regression technique (SAS Institute Inc., 1988) to the function:

$$D = c + b [1 - \exp(- at)] \quad (6)$$

where D = amount of dispersed material measured (g g⁻¹), t = time of sonification (s), c = amount of dispersed material before sonification (g g⁻¹), and a and b are constants. Breakdown of the soil sample was assumed to be completed when 99% of the ultrasonically dispersible material had dispersed. Substituting this value into Equation (6) provided the sonification time when effective dispersion ceased (t_d).

To decrease the possible detrimental effects of high temperature on soil structural stability, samples were sonified using a series of shorter sonifications, each less than 180 s, to ensure that the maximum temperature of the suspensions did not exceed 35 °C. Samples were placed in an ice bath to lower their temperature to approximately 20 °C before the next sonification.

Calculation of the energy balance components

The rate of energy consumption associated with heating the suspension ($E_h/\Delta t$) may be calculated by re-writing Equation (2) as:

$$\frac{E_h}{\Delta t} = (m_w c_w + m_s c_s + W_v) \frac{\Delta T}{\Delta t} \quad (7)$$

where $\Delta T/\Delta t$ is the rate of increase in temperature with sonification time (t). Similarly, the rate of energy lost from the system by conduction ($E_c/\Delta t$) can be described by:

$$\frac{E_c}{\Delta t} = (m_w c_w + m_s c_s + W_v) \frac{\Delta T_c}{\Delta t} \quad (8)$$

where $\Delta T_c/\Delta t$ is the slope of the cooling characteristic of the system. Calculations for $E'_h/\Delta t$ and $E'_c/\Delta t$ are similar but conducted on the same samples after complete dispersion.

Equations (7) and (8) assume that the change in recorded temperature is uniform throughout the entire suspension. However, as the temperature of the suspension is measured at a point and the suspension is subject to turbulence, large variations occur in the calculation of $\Delta T/\Delta t$ if temperature observations over short time intervals are utilized. Assuming that the temperature at a point deviates from the overall suspension temperature according to a normal distribution, a better estimate of the overall suspension temperature for each point in time is obtained from a moving average over several recordings. Similarly, by conducting a linear regression on the moving average recordings, $\Delta T/\Delta t$ can be obtained directly from the slope of the regression for each time interval. Ignoring the initial period of temperature probe response time, $\Delta T/\Delta t$ will be similar for both the recorded and actual suspension temperatures but offset by the period of lag. As the suspension was observed to fully circulate around the container within a 20-s period, this period was adopted for the moving regression analysis. The rapid response time of the temperature probe and the use of a 20-s regression period to calculate changes in temperature reduces the error associated with temperature lag, and so no adjustment was conducted on the temperature data to account for lag.

To obtain a continuous measure of dispersive energy consumption throughout sonification, six replications of each treatment were used with an initial sonification period of either 90 s (3 replicates) or 180 s (3 replicates). Subsequent sonifications were for a period of 180 s. The calculation of dispersive energy consumed during the first 30 s in each sonification was disregarded because of the time lag of the temperature probe and the initial non-uniform mixing of soil within the suspension. For the calculation of the total dispersive energy E_d , the dispersive energy consumption for the zero to 30 s period of the initial sonification was assumed to be similar to the 30–60 s period.

Suspension temperature changes recorded during sonification at times greater than t_d were used to calculate the power $[(E_h + E_c)/\Delta t]$ dissipated into the suspension. Preliminary trials showed significant linear relationships ($P < 0.05$) between the temperature of the suspension and the actual probe power output measured calorimetrically in the suspension. This was presumably a result of changes in the suspension viscosity and the acoustic coupling associated with variation in the suspension temperature. To correct for this effect, the rate of dispersive energy consumption was calculated as the difference between the power measured during dispersion and the power measured at the same temperature after complete dispersion of the sample.

Soil dispersion characteristic curves for each soil were obtained from the relationship between the quantity of $< 2 \mu\text{m}$ and $< 20 \mu\text{m}$ material produced by sonification with the total energy consumed by dispersion. Exponential curves in the same form as Equation (6) (where t is replaced by $L = \text{energy consumed by dispersion [J g}^{-1}\text{]}$) were fitted to the data.

Measurement of soil stability

A modification of the end-over-end shaking technique (So & Cook, 1987; Cook, 1988) was used to determine the stability of the soils. The air-dried equivalent of 50 g oven-dried soil was immersed in 1000 cm³ deionised water (equilibrated at 20°C) within a perspex sedimentation cylinder (internal diameter 70 mm, total volume 1425 cm³). The cylinders were then placed on an end-over-end shaker rotating at 20 rpm for a period of 30 min. Following the shaking, the suspensions were mixed thoroughly and allowed to settle in a constant temperature environment. After the appropriate period, $< 2 \mu\text{m}$ and $< 20 \mu\text{m}$ equivalent diameter material was sampled using the pipette withdrawal method.

RESULTS

The physical and chemical properties of the experimental soils are presented in Table 1. An increase in the total energy applied to the soil suspension during sonification resulted in increased breakdown of the aggregates until all aggregates had been completely dispersed (Fig. 2). For all soils, breakdown of the $> 20 \mu\text{m}$ aggregates was more rapid than the 2–20 μm aggregates. The fitted exponential curves (Equation 6) accounted for more than 85% of the variation in dispersed material with applied ultrasonic energy. No further dispersion was achieved after periods of sonification ranging from 279 to 640 s (Table 1).

Table 1. Physical and chemical properties of the vertisol soils used in the experiment

Soil name	Clay	Silt	Sand	Exchangable cations (mmol _c kg ⁻¹)				Organic C (g g ⁻¹)	Inorganic C (g g ⁻¹)	t _d ^a (s)	E _d ^b (J g ⁻¹)
	<2 µm	2-20 µm	>20 µm	Ca	Mg	Na	K				
PW2	0.67	0.10	0.23	539	211	37.0	22.6	0.0164	0.00074	384	7.3 (±2.6)
PRA1	0.68	0.08	0.24	304	280	23.3	26.2	0.0198	0.00003	279	20.0 (±6.1)
PRA2	0.65	0.11	0.24	321	294	20.4	19.1	0.0182	0.00016	451	23.0 (±6.5)
PA2	0.43	0.14	0.43	435	156	11.4	14.9	0.0192	0.00096	527	27.8 (±6.2)
PV1	0.52	0.14	0.34	289	142	14.7	12.6	0.0155	0.00000	281	11.8 (±3.9)
PP3	0.45	0.10	0.45	239	157	43.0	13.0	0.0122	0.00039	640	34.6 (±3.9)
PH2	0.45	0.06	0.49	377	175	37.9	11.7	0.0134	0.00008	407	23.6 (±4.8)

^aPeriod of sonification at 8.9 (±0.3) W required to produce 99% dispersion of the dispersible material.

^bTotal dispersive energy (±SE) required to produce 99% dispersion of the ultrasonically dispersible clay-sized material.

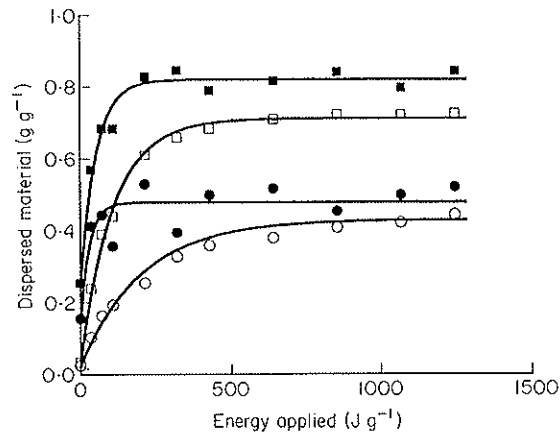


Fig. 2. Dispersion curves for the PA2 (○ < 2 μm, ● < 20 μm) and PRA1 (□ < 2 μm, ■ < 20 μm) soils.

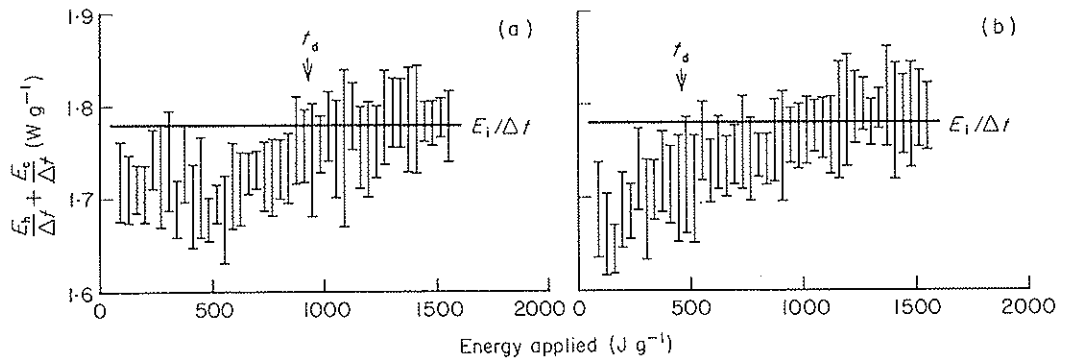


Fig. 3. Power consumed by heating and heat loss from the system during sonification of (a) PA2 and (b) PRA1 soils. Bars indicate 95% confidence intervals.

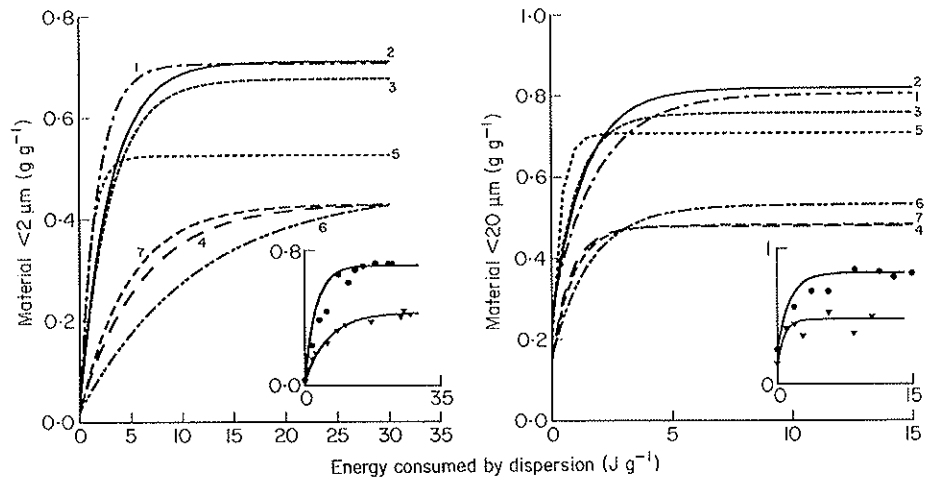


Fig. 4. Soil dispersion characteristic curves for seven vertisol soils (1 PW2, 2 PRA1, 3 PRA2, 4 PA2, 5 PV1, 6 PP3, 7 PH2). Insert shows actual data for PA2 (▼) and PRA1 (●).

Table 2. Calculated applied and dispersive energy required to produce the dispersion equivalent to 30 min end-over-end shaking

Soil	End-over-end shaking Size (μm)	D (g g^{-1})	Dispersive energy ^a (J g^{-1})				Applied energy ^b (J g^{-1})				Significance
			x_{best}	95% range ^c		Significance	x_{best}	95% range ^c		Significance	
				lower	upper			lower	upper		
PW2	<2	0.108	0.21	0.15	0.31	*	17.29	13.90	21.86	*	
	<20	0.421	0.61	0.54	0.70		26.93	22.36	33.27		
PRA1	<2	0.142	0.52	0.44	0.62	ns	18.67	16.61	21.21	ns	
	<20	0.467	0.66	0.51	0.89		24.47	18.21	35.45		
PRA2	<2	0.106	0.36	0.30	0.44	ns	20.77	17.78	24.42	ns	
	<20	0.431	0.48	0.37	0.67		31.48	23.23	46.10		
PA2	<2	0.049	0.37	0.30	0.45	ns	12.30	9.65	16.33	ns	
	<20	0.288	0.42	0.20	3.01		15.78	7.03	223.92		
PV1	<2	0.083	0.14	0.11	0.20	ns	14.89	11.71	19.82	ns	
	<20	0.329	0.12	0.09	0.21		12.01	8.06	26.02		
PP3	<2	0.080	1.62	1.00	3.17	ns	35.29	17.84	54.34	ns	
	<20	0.306	1.18	0.67	3.02		11.98	9.19	45.21		
PH2	<2	0.085	0.84	0.57	1.41	ns	27.71	19.05	45.50	ns	
	<20	0.323	0.67	0.45	1.16		23.77	15.54	43.77		

^aEquivalent dispersive energy required to produce the same amount of dispersed material as 30 min end-over-end shaking.

^bEquivalent ultrasonic applied energy required to produce the same amount of dispersed material as 30 min end-over-end shaking.

^cExplanation in text.

* = Significant difference ($P < 0.05$).

ns = Non-significant difference ($P > 0.05$).

Figure 3 shows that significantly less ($P < 0.05$) energy was involved in heating and heat loss ($E_h/\Delta t + E_c/\Delta t$) from the system during dispersion than after complete dispersion, with the difference being due to the consumption of energy for dispersion. The total amount of dispersive energy required to break down 99% of the potentially dispersible material differed significantly ($P < 0.05$) between soils (Table 1). Soil dispersion characteristic curves shown in Fig. 4 accounted for more than 85% of the variation in the data. To avoid confusion, the data points are not shown for all soils; however, inserts show actual values and regressions fitted for the PRA1 and PA2 soils.

Confidence-limit regressions were obtained for each SDCC and dispersion curve by using the asymptotic 95% confidence limits for the fitted parameters of Equation (6). Estimates of the total applied and dispersive energies required to produce the equivalent amount of dispersion from the end-over-end technique were subsequently obtained by substituting the $< 2 \mu\text{m}$ and $< 20 \mu\text{m}$ results into the confidence-limit regressions of the SDCC and dispersion curves, respectively (Table 2). As these regressions were obtained using the amount of dispersion as the dependent variable, the probability distribution of the estimates obtained is not normally distributed throughout the range. Thus, although this technique estimates the energy requirement with a 95% probability, the best estimate (x_{best}) may not be centrally located within the range.

Table 2 shows that the total applied ultrasonic energy and dispersive energy required to produce the same amount of $< 2 \mu\text{m}$ and $< 20 \mu\text{m}$ material as the end-over-end shaking is not significantly different ($P < 0.05$) between the two fractions except for the PW2 soil. As expected, there was no significant difference ($P < 0.05$) in the total energy applied to the seven soils. However, the dispersive energy required to produce the equivalent end-over-end dispersion for the PP3 soil was significantly greater than for PV1 and PRA2 soils. No other significant difference in dispersive energy was observed between the soils.

DISCUSSION

Dispersive energy

In North's (1976) calorimetric technique, it was assumed that the energy dissipated in pure water and a soil-water system were the same. However, differences in the viscosity and elasticity of these systems could affect the efficiency of acoustic coupling. By calculating the energy application rate as that applied into the fully dispersed suspension, differences due to changes in the acoustic coupling are avoided.

The calculation of dispersive energy consumption throughout sonification also has distinct advantages over North's (1976) original method. North assumed that a constant proportion of energy is consumed by dispersion throughout the period of sonification, which requires only a single measurement of suspension temperature before and after sonification. The continuous measurement of temperature throughout sonification in this experiment has shown that the rate of dispersive energy consumption is not necessarily constant (Fig. 3). These results support Koenig's (1978) criticism of North's work that energy consumed by dispersion is dependent on the number and strength of bonds sheared and should therefore be unique for each soil. In this experiment, the rate of dispersive energy consumption during aggregate breakdown (Fig. 4) and the total dispersive energy consumed by complete dispersion (Table 1) have been shown to be characteristic of each soil and are presumably dependent on the energy of the bonding mechanisms involved.

Error analysis

Many errors associated with using separate samples for the determination of the standard energy applied to the system have been eliminated by the calculation of energy application after complete dispersion for each sample. Hence, substituting Equations (7) and (8) into Equation (5), the rate of dispersive energy consumption may be described as:

$$\frac{L}{\Delta t} = (m_w c_w + m_s c_s + W_w) \left(\frac{\Delta T'}{\Delta t} + \frac{\Delta T'_c}{\Delta t} - \frac{\Delta T}{\Delta t} - \frac{\Delta T_c}{\Delta t} \right) \quad (9)$$

Propagation of measurement uncertainties for values in the first bracketed term produced variances of approximately 0.5% in the calculation of this term. Uncertainty for each sub-term in

the second set of brackets was calculated as the variance of the slope parameter estimate from the linear regression of temperature data (Taylor, 1982). In general, individual variances in slope determination using a regression period of 20 s were less than 1%. However, as the second bracketed term was calculated by difference, the overall variance in this term was found to be approximately 20% of the calculated value. Thus, as the measurement error associated with the first bracketed term is negligible, the rate of dispersive energy consumption ($L/\Delta t$) can be calculated with an approximate variance of 20%.

Calculation of E_p as the total sum of dispersive energy used, and the overall variance as the square root of the sum of the individual variances squared (Taylor, 1982), shows that the variance of E_p attributable to the measurement errors is generally less than 0.5 J g^{-1} (<10%). Thus, measurement errors in E_p are small compared to observed E_p values (Table 1) suggesting that this technique is able to identify the consumption of energy for dispersion. These measurement errors are also considerably smaller than the observed variability in total dispersive energy (Table 1), suggesting that sample variability is the major source of variation in the dispersive energy results.

Comparison of dispersion techniques

As each soil was subjected to the same amount of end-over-end shaking, it is expected that the total energy applied to each soil would also be the same. This is consistent with the equivalent total ultrasonic energies applied (Table 2) which show no significant differences between the soils. It is interesting to note that the simple calculation of 1 kg falling 11 cm (the maximum distance of movement of the centre of gravity) 1200 times (2 falls/rotation) represents the application of approximately 26 J g^{-1} by the end-over-end shaking treatment. As this value is within the range of x_{best} values presented in Table 2, it suggests that a similar amount of total energy is required to be applied by both techniques to produce this level of dispersion.

It seems reasonable to expect that a particular soil will need the same dispersive energy requirement regardless of the method of energy application employed. Thus, the SDCC should be a characteristic of the soil and independent of the method of measuring the energy consumed by dispersion. Similarly, the equivalent dispersive energy requirement (Table 2) should represent the actual amount of energy consumed by aggregate breakdown and dispersion during the end-over-end shaking treatment. Thus, significant differences in the dispersive energy consumed by the PP3 soil and the PV1 and PRA2 soils during the end-over-end shaking treatment may represent differences in either the quantity or type of bonding mechanisms operating in these soils at this level.

The amount of $<2 \mu\text{m}$ and $<20 \mu\text{m}$ material released in the end-over-end shaking treatment for each soil was produced by the same energy application. Thus, the applied ultrasonic energy required to produce an equivalent amount of dispersion for these two fractions should also be the same. The difference observed between the equivalent dispersive energies for $<2 \mu\text{m}$ and $<20 \mu\text{m}$ material in the PW2 soil suggests that the end-over-end technique effectively breaks down aggregates for this soil into silt-sized material, but is inefficient at breaking the silt-sized material into individual clay particles. This has resulted in an overestimation of the equivalent dispersive energy required to produce the $<20 \mu\text{m}$ material and an underestimation of the dispersive energy required to produce the equivalent amount of $<2 \mu\text{m}$ material in this soil.

The quantity of dispersed material produced by the end-over-end technique (Table 2) is small compared to the potentially dispersible material of the samples. Cook & So (1987) and Cook *et al.* (1992) have shown that dispersive indices derived using 30 min of end-over-end shaking are related to field soil properties and behaviour. Therefore, the input energies that affect soil dispersion and soil behaviour in the field are relatively small compared to the requirement for complete breakdown. This is consistent with North's (1979) conclusion that the specific stability index (analogous to E_p as measured in these experiments) provided little indication of soil management potential. However, the calorimetric technique has been shown to identify significant differences between soils for dispersive energy consumption throughout aggregate breakdown and should provide a better indication of the effect of field energies on soil dispersion and behaviour. Further investigations will be necessary to identify relationships between the SDCC and soil management potential.

In conclusion, this paper has shown that the sonic probe in combination with the calorimetric technique can be used to measure the total energy applied to a soil-water system and the component consumed by the breakdown and dispersion of soil aggregates.

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