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Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology

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Summary

Crusting and erosion of cultivated soils result from aggregate breakdown and the detachment of soil fragments by rain, and the susceptibility of soil to these processes is often inferred from measurements of aggregate stability. Here, theories of aggregate breakdown are reviewed and four main mechanisms (i.e. slaking, breakdown by differential swelling, mechanical breakdown by raindrop impact and physico–chemical dispersion) are defined. Their relative importance depends on the nature of the rain, as well as on the soil's physical and chemical properties. The relations between aggregate breakdown, crusting and water erosion are analysed, and existing methods for the assessment of aggregate stability are reviewed. A unified framework for the measurement of aggregate stability is proposed to assess a soil's susceptibility to crusting and erosion. It combines three treatments having various wetting conditions and energies (fast wetting, slow wetting, and stirring after pre-wetting) and measures the resulting fragment size distribution after each treatment. It is designed to compare different soils, or different climatic conditions for a given soil, not to compare time-dependent changes in that soil.

Stabilité structurale et évaluation de la sensibilité des sols à la battance et à l'érosion: I: Théorie et méthologie

Résumé

La battance et l'érosion des sols cultivés résultent essentiellement de la désagrégation des mottes de terre et du détachement de fragments sous l'action des pluies. La mesure de la stabilité structurale est donc souvent utilisée pour évaluer la sensibilité des sols à la battance et à l'érosion hydrique. On peut distinguer quatre principaux mécanismes de désagrégation (l'éclatement, la désagrégation par gonflement différentiel, la désagrégation mécanique par l'impact des gouttes de pluie, la dispersion physico-chimique) dont l'importance relative dépend des caractéristiques des pluies et des sols. Après un rappel sur ces mécanismes, cet article analyse leurs relations avec la battance et l'érosion puis décrit les caractéristiques des principales méthodes existant. On propose, à partir de cette analyse, un cadre méthodologique cohérent permettant d'évaluer la stabilité structurale des sols en relation avec la battance et l'érosion. La méthode combine trois traitements correspondant à différentes conditions d'humectation et différents niveaux d'énergie (humectation rapide par immersion, humectation lente par capillarité et agitation mécanique après préhumectation). La méthode est adaptée pour comparer le comportement intrinsèque de différents sols ou d'un sol donné dans différentes conditions climatiques, ainsi que pour tester l'influence de traitements ou amendements sur la stabilité structurale, mais pas pour tester les variations de stabilité dans le temps pour un sol donné.

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Table 1 Characteristics of some of the main methods for testing aggregate stability (several of these methods include various pretreatments)

Type of treatment	Form of sample	Expression of the result	Authors
	3–5 mm	MWD*	Yoder (1936)
	<2 mm	%>200 μm	Hénin *et al.* (1958)
Wet sieving	whole soil	change in MWD	De Leenheer & De Boodt (1959)
	1–2 mm	%>250 μm	Kemper & Rosenau (1986)
	2–3.4 mm	MWD	Churchman & Tate (1987)
	1–2 mm	%>250 μm	Pojasok & Kay (1990)
	4–5 mm	time to breakdown	Low (1967)
Raindrops	2–9 mm	MWD	Young (1984)
or rainfall	5–8 mm	time to breakdown	Farres (1987)
	whole soil	%<125 μm	Loch (1994)
Ultrasonic	4–5 mm	dispersion rate	Edwards & Bremner (1967)
dispersion	4–5 mm	inter-aggregate pore volume	Grieve (1980)
Immersion	3–5 mm	qualitative	Emerson (1967)
Dry sieving	<4 mm	MWD	Kemper & Chepil (1965)

Introduction

Dozens of methods for measuring the stability of soil aggregate have been used around the world since the late 1930s (Yoder, 1936; Hénin *et al.*, 1958; Emerson, 1967) (Table 1). This reflects both a sustained interest in this property and the lack of a satisfactory standard methodology. Aggregate stability influences several aspects of a soil's physical behaviour. In particular, water infiltration and soil erosion depend strongly on it (Bryan, 1968; De Ploey & Poesen, 1985). Aggregate breakdown, however, depends on many factors, and the processes involved are so numerous and complex that no general agreement currently exists about the measurement of this property and its relation to crusting and erosion (Boiffin, 1984; Loch, 1994). The relations between crusting and erosion were recently investigated by Hairsine & Hook (1995) who concluded that there was much in common between both processes, and that erosion rates were dominantly controlled by processes of aggregate breakdown. Emerson & Greenland (1990), in a comprehensive review of soil aggregate formation and stabilization defined two processes of aggregate breakdown: slaking and dispersion. Other authors, more concerned with field observations, consider raindrop impact to be the main cause of structural degradation at the soil surface (Nearing & Bradford, 1985). Therefore, the problem needs to be approached from a theoretical as well as a methodological point of view.

The aims of this paper are: (i) to review the theories about the mechanisms of aggregate breakdown and the soil properties influencing aggregate stability; (ii) to discuss the relations between aggregate stability, crusting and erosion; (iii) to present and discuss the characteristics of the main methods for measuring aggregate stability; and (iv) to propose a unified methodological framework for such measurement.

A subsequent paper (Le Bissonnais & Arrouays, 1997) will deal with the validation of the proposed method and its application in the investigation of the effects of forest clearing and continuous maize cropping on the aggregate stability of humic loamy soils.

The mechanisms of aggregate breakdown

Aggregate breakdown by water may result from a variety of physico-chemical and physical mechanisms and may involve different scales of soil structure from clay particle interactions to the macroscopic behaviour of aggregates (Tisdall & Oades, 1982; Elliott, 1986; Oades & Waters, 1991). Four main mechanisms can be identified from the various reviews already available: (i) slaking, i.e. breakdown caused by the compression of entrapped air during wetting (Panabokke & Quirk, 1957; Boiffin, 1984); (ii) breakdown by differential swelling (Kheyrabi & Monnier, 1968; Le Bissonnais, 1989); (iii) breakdown by raindrop impact (Nearing & Bradford, 1985); (iv) physico–chemical dispersion due to osmotic stress (Emerson, 1967; Shainberg, 1992; Sumner, 1992).

These mechanisms differ in many ways (Table 2): in the nature of interparticle bonds and the energy involved in their disruption (Kemper & Rosenau, 1984; Truman *et al.*, 1990), in the physical and chemical conditions required for disaggregation, in the kinetics of the breakdown process, in the type of soil properties influencing the mechanism, and in the nature and size distribution of the breakdown products (Farres, 1987; Le Bissonnais, 1988; Römkens *et al.*, 1990; Chan & Mullins, 1994).

Breakdown by compression of trapped air: slaking

Slaking is caused by the compression of air entrapped inside aggregates during wetting (Yoder, 1936; Panabokke & Quirk,

Table 2 Characteristics of the main breakdown mechanisms

Mechanism	Slaking	Breakdown by differential swelling	Breakdown by raindrop impact	Physico-chemical dispersion
Type of forces involved	Internal pressure by air entrapment during wetting	Internal pressure by clay differential swelling	External pressure by raindrop impact	Internal attractive forces between colloidal particles
Soil properties controlling the mechanism	Porosity, wettability, internal cohesion	Swelling potential, wetting conditions, cohesion	Wet cohesion (clay, organic matter, oxides)	Ionic status, clay mineralogy
Resulting fragments	Microaggregates	Macro and and microaggregates	Elementary particles	Elementary particles
Intensity of the disaggregation	Large	Limited	Cumulative	Total

1957; Hénin *et al.*, 1958; Emerson, 1967). It occurs when dry aggregates are immersed in water or rapidly wetted. The effect of trapped air depends on the volume of air inside the aggregates, on the rate of wetting (Concaret, 1967; Loch, 1994), and on the shear strength of wet aggregates (Nearing & Bradford, 1985). Slaking occurs even without any shaking of soil in water, although shaking increases the effect of slaking because of additional mechanical breakdown or dispersion. Panabokke & Quirk (1957), Le Bissonnais (1988) and Truman *et al.* (1990) found that slaking decreases as the initial moisture content increases until saturation is reached (Fig. 1). This is due to the reduction of the volume of air that is entrapped during wetting and also to the reduction of gradients of matric potential. Figure 1 also shows that, in the range of 100–300 g kg^{-1} of clay content, breakdown decreases when clay content increases.

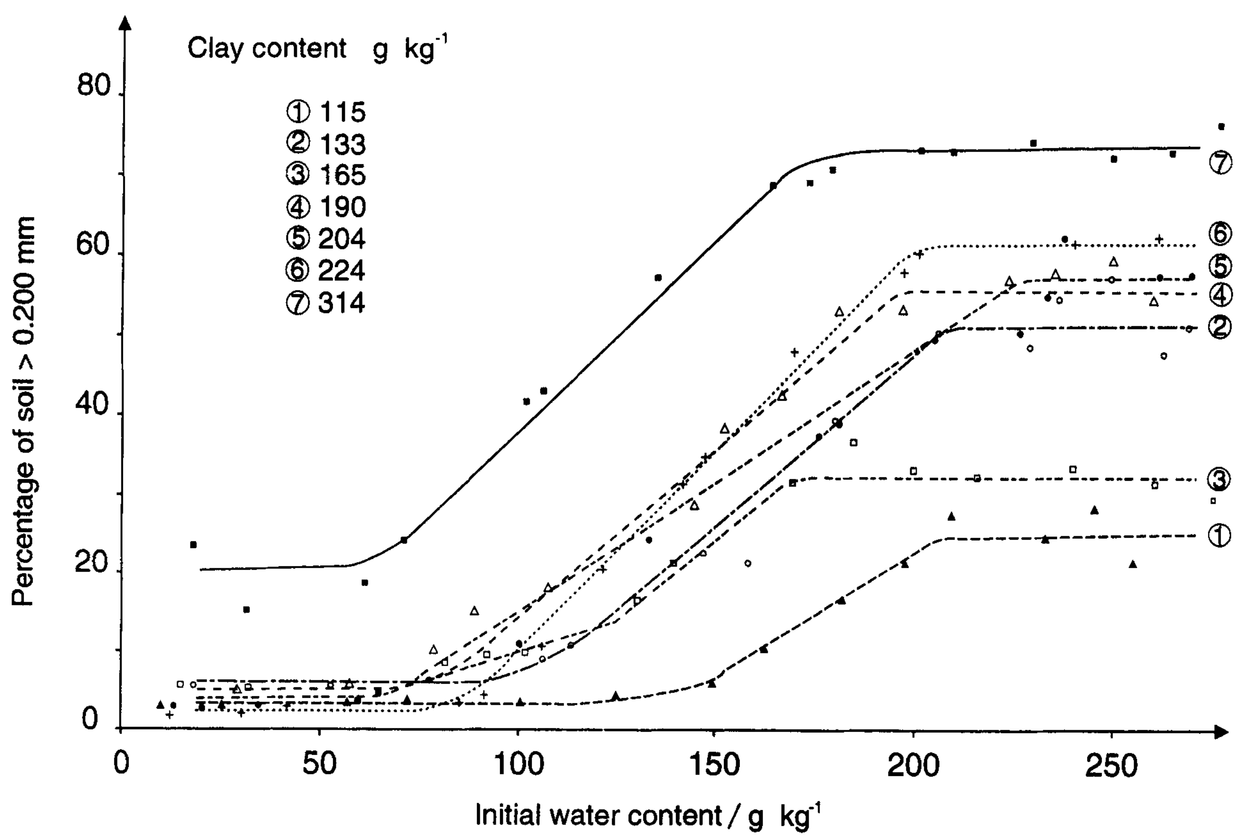

Fig. 1 Aggregate stability measured by the method of Hénin *et al.* (1958) (percentage of fragments >200 μm after immersion of aggregates in water and sieving with the Hénin apparatus), as a function of water content and clay percentage, for various cultivated silty and loamy soils from northern France (after Le Bissonnais, 1988).

The fragments resulting from slaking are mainly microaggregates, and they increase in size with increasing clay content. This can be explained according to the model of textural porosity (Fies & Stengel, 1981): the clay volume and the resistance of clay bonds between skeleton grains increase with clay content, so the elementary assemblages of primary particles are bigger.

Breakdown by differential swelling

Differential swelling and shrinkage during wetting and drying of clay soil results in a microcracking of aggregates (Kheyrabi & Monnier, 1968). It depends on the same properties as slaking, including the rate of wetting, and it produces microaggregates which are about the same size and type as microaggregates resulting from slaking of initially wet soils (Le Bissonnais, 1989). However, we make the distinction between the two mechanisms because physical processes are different, although some authors use the word 'slaking' for both mechanisms. They involve different types of soil in terms of clay content (Chan & Mullins, 1994), and it is important to note that breakdown by slaking decreases as clay content increases, whereas breakdown by differential swelling increases with increasing clay content. The consequences of breakdown by differential swelling (microcracking) on infiltration are less severe than those of slaking or dispersion because of the larger size of resulting fragments. However, microcracking may accelerate the formation of structural crusts by reducing the mean aggregate size (Le Bissonnais & Le Souder, 1995).

Mechanical breakdown by raindrop impact

Mechanical breakdown of aggregates by raindrop impact usually occurs in combination with the other mechanisms if the kinetic energy of raindrops is great enough (Al-Durrah & Bradford, 1982; Boiffin, 1984; Nearing *et al.*, 1987; Bradford & Huang, 1992). The importance of this effect is clearly demonstrated by the role of vegetation cover or mulch which protect the soil surface against such impact. Mechanical breakdown by raindrop impact plays a dominant role on wet soils because the aggregates are weaker when the soil is wetter. Also, under 'undrained' conditions, the compressive stress of the raindrop impact is transformed into lateral shear stress that causes the fragments to detach and project (Al-Durrah & Bradford, 1982). Therefore, raindrop impact not only detaches but also displaces previously detached fragments. This mechanism is called the splash effect (Ellison, 1945; Farres, 1987). Because very stable macroaggregates can be moved by splash, a discrepancy between aggregate stability and splash measurement under rainfall may be expected. However, for many soils, aggregate breakdown and crusting may occur even without mechanical impact, simply by slaking or dispersion.

The fragments resulting from raindrop detachment are generally small, being either elementary particles or small microaggregates (< 100 μm).

Physico-chemical dispersion

Physico-chemical dispersion results from the reduction of the attractive forces between colloidal particles while wetting (Emerson, 1967; Sumner, 1992). Stability or dispersion depends on cation size and valence. Polyvalent cations cause flocculation, whereas the monovalent cations cause dispersion. Dispersion is affected by the electrolyte concentration (EC) of the soil solution (Agassi *et al.*, 1985), the EC of applied water, and by mechanical disturbance from raindrop impact or shaking (Emerson, 1967). These variables must be controlled when measuring soil dispersion. Dispersion is also facilitated by slaking and by swelling.

Dispersion depends mainly on the exchangeable sodium percentage (ESP) of the soil. The defining characteristic of dispersion is the production of elementary particles rather than microaggregates. Therefore, dispersion is one of the most effective processes of aggregate breakdown, and it greatly increases the effect of the others (Bresson & Boiffin, 1990). Dispersion generally induces very fast crusting, slow infiltrability and great mobility of particles in water (Ben-Hur *et al.*, 1992). However, Abu-Sharar *et al.* (1987) showed that sometimes dispersion has to be associated with slaking to reduce hydraulic conductivity because dispersed clay particles are mobile, easily illuviated and not able to clog large conducting pores. This result highlights the need to measure the fragment size distribution rather than only one size class in aggregate stability tests.

The main soil properties influencing aggregate stability

The main soil properties influencing aggregate stability and erosion have been well known since the early works of Yoder (1936), Hénin (1938), Kemper & Koch (1966), Wischmeier & Mannering (1969), but some subsequent studies have produced contradictory results. The properties that are most often mentioned are soil texture, clay mineralogy, organic matter content, type and concentration of cations, sesquioxide content, and $CaCO_3$ content, with multiple interactions between these properties that can modify their individual influence. Emerson & Greenland (1990) give a complete review of those effects. Of these soil properties, three play a major role in aggregate stability. They are: (i) ESP (Emerson, 1967; Kazman *et al.*, 1983; Frenkel *et al.*, 1978; Shainberg, 1992), (ii) iron and aluminium oxides and oxyhydroxides that cement aggregates, particularly for tropical and lateritic soils (Römkens *et al.*, 1977; Le Bissonnais & Singer, 1993), and (iii) organic matter which is a bonding agent between mineral soil particles (Monnier, 1965; Tisdall & Oades, 1982; Churchman & Tate, 1987; Chenu, 1989; Haynes & Swift, 1990), which protect the surface against raindrop impact, improve water infiltration and which may impart hydrophobic characteristics that reduce wetting rate and slaking (McGhie & Posner, 1980; Sullivan, 1990; Jouany *et al.*, 1992).

In conclusion, the effect of some soil properties on aggregate stability and erodibility has been well established by experimental study, and there is frequently a relation between a given soil property and aggregate breakdown (Emerson & Greenland, 1990). These relations, however, do not apply to all soils in all circumstances.

The relations between aggregate stability, crusting and erosion

To use aggregate stability measurements to assess soil crustability and water erodibility, the relations between these processes and stability must be examined carefully. Soil erodibility may be defined as the inherent susceptibility of soil to detachment and transport by rain and runoff (Ellison, 1945) (the problem of wind erosion will not be examined in this paper). Relations exist between aggregate breakdown, which reduce the size of soil fragments, and crusting and erosion (De Ploey & Poesen, 1985; Le Bissonnais *et al.*, 1993; Hairsine & Hook, 1995). Knowledge of these processes can be integrated into a single framework (Fig. 2).

Erosion and crust formation

For most cultivated lands erosion results from runoff caused by the decrease of infiltration rate following rain, which is often accompanied by surface sealing (Poesen & Govers, 1986; Moore & Singer, 1990; Le Bissonnais, 1990). The infiltration rate may decrease to as little as 1 mm h^{-1}. Another effect of sealing is the reduction of surface roughness that results in smaller depressional storage and in more uniform flow over the surface (Hairsine & Hook, 1995).

Two main morphological types of crust can be distinguished (West *et al.*, 1992). Structural crusts are formed by a reorganization with little displacement of fragments, and without sorting and sedimentation. They result from the gradual packing and coalescing of particles and small aggregates, which are mainly produced by slaking and microcracking. Depositional or sedimentary crusts result from fragment and particle displacement and sorting under ponding conditions. The mechanisms are mainly dispersion and mechanical breakdown by raindrop impact. Bresson & Boiffin (1990) showed that these two crust morphologies correspond to two successive stages in a general pattern of crust development: sealing of the surface by a structural crust, and then formation of a depositional crust. Structural crusts, however, are generally formed during the preponding phase, whereas depositional crusts and erosion are coincident. A distinction between the various mechanisms of breakdown may help to explain the dynamics of surface crusting and erosion. For example,

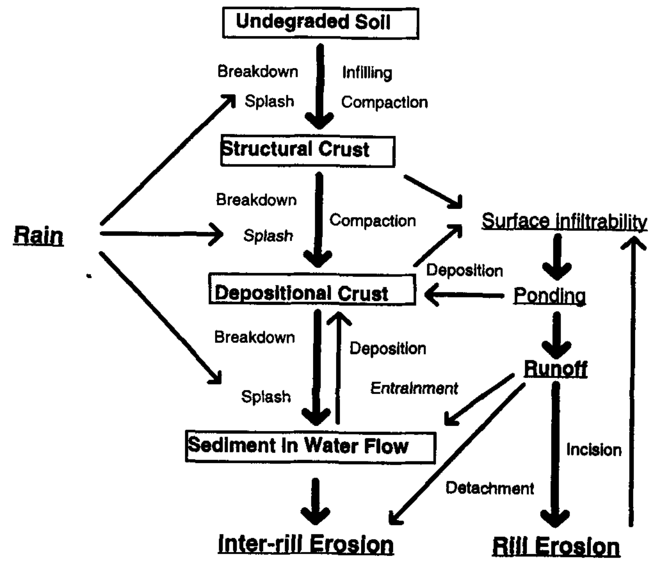

Fig. 2 Diagram of the relationships between aggregate breakdown, crusting and erosion (after Le Bissonnais, 1990; Hairsine & Hook, 1995).

Shainberg *et al.* (1992) observed that slaking occurred rapidly under simulated rainfall and was followed by clay dispersion and surface compaction that formed the surface seal. Miller & Baharuddin (1986) found good relations between soil dispersibility and infiltration and erosion.

Soil fragments release

Loch (1994) and Le Bissonnais (1988) emphasized the importance of the production of fragments <100 μm. Whether they are primary particles or microaggregates, when packed together, they result in pores no larger than about 15 μm. It can be shown from Poiseuille's equation and the measurements of raindrop pressure (Nearing *et al.*, 1987), that for pores <15 μm, frictional effects reduce water penetration (Loch, 1994). The results of Norton *et al.* (1986) from image analysis and of Le Bissonnais *et al.* (1989) from mercury porosimetry supported this theoretical conclusion and showed that if all the pores are <15 μm then infiltration ceases. Farres (1987) also stressed that the magnitude of erosion is not just controlled by the breakdown, but also by the size of the detached fragments.

In addition to being the primary cause of crusting, aggregate breakdown is responsible for the production of microaggregates and particles, which are easily transported by runoff and splash. This second effect of breakdown is particularly important in interrill erosion, where the runoff detachment capacity is limited. In fact, the size of the detached fragments determines both the physical properties of the crust (porosity and infiltration) and the transportability of fragments. Hairsine & Rose (1991), Proffitt *et al.* (1991) and Hairsine & Hook (1995) showed that interrill erosion results from a combination of detachment, transport, deposition, re-detachment and re-deposition. The sorting of material depends mainly on the settling velocity of fragments, which is closely related to their size. It is therefore important that measurement of aggregate stability gives information about the size distribution of resulting fragments.

Space and temporal dynamics

Water erosion is generally divided into two components: rill and interrill erosion. Sealing may affect both because they both depend on runoff, splash, transport and detachment capacity. Furthermore, these two components of erosion are generally closely associated in the field. However, this effect may be complicated because crusting may increase soil shear strength as well as resistance to detachment and to rill formation (Bradford *et al.*, 1987; Poesen & Bryan, 1989). Therefore, opposed effects may occur.

The following dynamics of interrill erosion have been observed by several authors (Bradford *et al.*, 1987; Farres, 1987): in the first stage, sealing increases the erosion rate by promoting runoff, and in the second stage, as the crust's mechanical resistance increases, the erosion rate decreases. Other experiments showed a linear relation between the rates erosion and runoff, indicating that the concentration of sediment in runoff was constant and therefore that detachment and transport of sediment were not limited (Le Bissonnais & Singer, 1993). The concepts of detachment-limiting erosion and transport-limiting erosion have been established to describe various interrill erosion situations (Foster, 1990). A more precise description of the processes would distinguish between the rôle of raindrop and flow in detachment and transport (Hairsine & Hook, 1995).

Limits of the relationship between crusting, erosion and aggregate breakdown

The evolution of a crust between rainfall events, through drying, freezing or biological effects, should be considered when studying erosion. Its final result may be completely independent of aggregate stability (Levy *et al.*, 1986; Roth & Helming, 1992).

Under heavy rain, runoff may occur without the formation of a seal, and large aggregates and coarse fragments may be transported and eroded. Clearly aggregate stability is not a good indicator of soil erodibility in this case. Therefore, no single method of stability analysis is sufficient to assess erosion risks in all circumstances.

Apart from the limits mentioned above, good conceptual and practical reasons exist for using measurements of aggregate breakdown to estimate soil crustability and erodibility. However, as stressed by Loch (1994), testing aggregate stability by sieving differs from field conditions because of the absence of raindrop impact and by the absence of the rest of soil. Both are important in surface crusting. Therefore, he proposed the use of rainfall simulation on large whole soil samples (which greatly differs from 'single raindrop on aggregate' tests) to test aggregate stability. Despite the validity of his arguments for using whole soil samples, the method requires a large amount of soil and is time-consuming. Some tests, that are easier to perform than rainfall simulation, may be used successfully as a first approach for many soil types, as follows.

Methods of aggregate stability measurement

The reason for the existence of many different methods for measuring aggregate stability can be explained, both by the existence of several mechanisms of breakdown, and for methodological reasons. Methods differ in one or more of the following aspects: (i) the characteristics of the sample subjected to the test, particularly its structure and moisture; (ii) the treatment applied to the sample; (iii) the measurement of the disaggregation, which is often not clearly separated from the treatment; and (iv) the expression of the result that may be more or less general and physically significant (calculation of various indices). Some of the main methods are listed in Table 1.

The possible choices for these various aspects are reviewed below. The aim of aggregate stability tests is to describe and rank soil behaviour under rain in a way that can be related to soil erosion. Tests should be easy to perform and be reproducible. They should also account for the various conditions that may occur at the soil surface, and they must be applicable to a large range of soils.

Characteristics of the sample subjected to the test

Because of the range of field conditions under which the samples are collected, the physical condition of samples needs to be standardized before testing so that different soils can be compared. The major factors are the moisture and the structure of the sample. The sample may be kept at field moisture content, wetted to a given moisture potential, or air dried. Numerous studies have shown that initial moisture content has a large influence on both aggregate breakdown and erosion (Truman *et al.*, 1990; Rasiah *et al.*, 1992; Le Bissonnais & Singer, 1992; Haynes, 1993). Slaking is reduced when aggregates are wet, but cohesion is also reduced. Keeping the sample at the field moisture content may give an accurate assessment of the soil behaviour at the time of sampling, but it does not allow comparison with samples at different moisture contents. To avoid this problem, it is preferable either to air dry the samples or to saturate them under controlled conditions prior to testing. However, the result may still be related, in part, to the antecedent moisture content and cropping history (Kemper & Rosenau, 1984; Caron *et al.*, 1992). Aggregate stability is always the result of a combination of permanent and transient properties.

The field structure of the sample may be preserved, or the soil can be sieved and separated into aggregate size classes.

De Leenheer & De Boodt (1959) used the entire soil sample and compared the fragment size distribution before and after their test. This method tests the actual field behaviour of the soil sample. However, most methods use specific soil size fractions (Hénin *et al.*, 1958) to allow a comparison between soils with different initial structures. It seems preferable, for standardization, to use an initial soil structure that is controlled to avoid confusion from previous uncontrolled disaggregation of the sample in the field or during sampling. In this sense, the use of calibrated aggregates is the best choice. The problem is that the tested sample must be representative of the whole soil, and the behaviour of calibrated aggregates may sometimes correspond to that of only a selected size fraction of the soil (Loch, 1994). To limit this inconvenience soil sampling should be made in the best possible conditions (e.g. after seed bed preparation), when the soil is already fragmented. The choice of the range of aggregate sizes does not seem to be a significant problem: most researchers tend to use aggregates within similar size ranges, between 2 and 10 mm diameter. Le Bissonnais (1988) found that the final fragment size distribution after immersion in water of fairly unstable silty soils was not affected by the size of initial aggregates in the range of 2–20 mm diameter. If it is difficult to collect aggregates from very weak and loose soil then the soil may directly be classified as very unstable.

The treatment applied to the sample

The treatments applied to soil samples vary greatly from sudden wetting by immersion in water, which may be followed by mechanical or ultrasonic dispersion (Yoder, 1936; Edwards & Bremner, 1967; Miller & Baharuddin, 1986), to application of raindrops (Low, 1967; Young, 1984). In most cases, the treatment consists of a combination of wetting and mechanical agitation, with various energies. Frequently the treatment and the measurement of the result are not clearly separated because the measurement itself involves energy and is destructive. Several methods combine different amounts of energy or rates of wetting, allowing different degrees of aggregation or mechanisms of breakdown to be distinguished. Some authors distinguish between aggregate stability tests (wet sieving) and dispersion tests (turbidimetry). The latter often involve greater rates of input of mechanical energy (shaking or ultrasonic energy) and are related to smaller scales of interactions (clay particles). Quirk & Murray (1991) make a distinction between macroscopic behaviour (aggregate stability) and microscopic behaviour (particle dispersion) in soil structure behaviour. However, actual soil behaviour involves a combination of both. The respective importance of structural stability at different size scales depends on the nature of the dominant stabilizing agent (Tisdall & Oades, 1982).

From this point of view it seems important that the amount of energy in the test should be comparable to the range of energies which may be encountered in natural conditions. However, there is evidence that not all soils can be tested accurately with the same amount of energy because of the large range of behaviours from weakly to strongly aggregated soils (Pierson & Mulla, 1989). It is therefore necessary to use various methods and to combine them in order to compare various soils. When using much energy the discrepancy between the test conditions and the field conditions must be mentioned, and it must be demonstrated that the discrimination between soils identified by the test accords with field observations.

The measurement of disaggregation and the expression of the result

Stability is frequently measured by wet sieving and recording the proportion of material exceeding an arbitrary size limit or by measuring the fragment size distribution after the treatment (Yoder, 1936; Hénin *et al.*, 1958). The problem is that the sieving is itself destructive and may be the main cause of aggregate breakdown, although it does not simulate the effect of raindrops. When aggregates are weak it discriminates poorly between soils. Other methods use a qualitative classification of the aggregates' behaviour (Emerson, 1967) or an indirect measurement: for example, the number of drops needed to break down aggregates through a sieve (Low, 1967), or the turbidity of a suspension (Pojasok & Kay, 1990).

The index expressing the result of the test depends on the method of measurement. It can be more or less general. When fragment size distribution is measured the mean weight diameter (MWD) (Kemper & Rosenau, 1986) or the median aggregate diameter (D50) (Truman *et al.*, 1990) may be determined.

Comparison between existing tests

Several papers have compared the results given by various methods. Results of tests are often (but not always) more or less correlated, but their ability to discriminate varies greatly. Pauwels *et al.* (1976) compared the results of several tests with soil loss measurements on small erosion plots under simulated rainfall, and only the test of Hénin *et al.* (1958) was correlated with soil loss. The method of De Leenheer & De Boodt (1959) was valuable only within a given textural class of soils. Chisci *et al.* (1989), measuring the aggregate stability of 13 Italian soils with various methods, observed all the indices were correlated and concluded that single-sieve indices might replace more complex methods. These authors even suggested that soil structural characteristics can be assessed with regression models using semipermanent soil characteristics. However, it may be expected that such regression models are not universal and cannot fit the entire range of soils. Matkin & Smart (1987), testing 70 different soils, observed both similarities and systematic differences between various tests. They also observed that qualitative tests were more subjective than those leading to indices, and then suggested that different tests may be applicable to different types of soil depending on their range of stability. Grieve (1980) concluded that both fast wetting and raindrop tests revealed large and consistent differences between sites, but the tests may have over-emphasized the decline in soil structural properties due to cereal cropping when compared with actual field behaviour. Results were closely related to organic carbon content. Grieve (1980) found that slow wetting tests yielded conflicting results. Imeson & Vis (1984) compared water-drop and ultrasonic methods with different amounts of energy input. Both methods produced similar size distributions of breakdown products for a wide range of soils and were found to be consistent and reproducible. Haynes (1993) compared measurements by wet sieving and turbidimetry and showed that the two methods had different responses to the effect of moisture content or cropping history. Perfect *et al.* (1990), in a study of temporal variation of aggregate stability, observed the same trend for both dispersible clay and >250 μm water stable aggregates.

The most common feature of the tests is wet sieving that combines almost all the potential breakdown mechanisms, even though it is considered to overemphasize slaking compared to rainfall conditions.

A unified methodological framework for the measurement of aggregate stability

Description of the method

In the light of the previous discussion, a unified methodological framework for the measurement of aggregate stability is proposed. It is not new, but it includes the most interesting aspects of current tests. The proposed method borrows from several existing methods, including those of Yoder (1936), Hénin *et al.* (1958), Grieve (1980), Kemper & Rosenau (1986) and many others. In order to be applicable to a large range of soils and conditions three treatments plus an additional dispersion test were selected to form the whole test.

The treatments were designed to allow: (i) a distinction between the elementary mechanisms of aggregate breakdown described above; (ii) the process of breakdown and measurement of the result of breakdown to be separated; and (iii) a summary of the results (index) that can be used directly to describe the soil behaviour. In accordance with the suggestion of Hénin *et al.* (1958), the methods use ethanol for several operations. The properties of ethanol and the characteristics of the interactions between soil and ethanol have two important consequences for the test: slaking is greatly reduced when dry aggregates are immersed in ethanol, and particles do not reaggregate during drying after wetting in ethanol or other organic solvents (Merzouk & Blake, 1991). The effects of ethanol on slaking are due to the modification of surface tension, viscosity and contact angle. Both the rate of wetting and swelling and the degree of swelling are reduced when aggregates pretreated with ethanol are immersed in water (Concaret, 1967; Emerson & Greenland, 1990).

Preparation of the sample

Particular attention must be paid to the field sampling. Because of seasonal variations in aggregate stability (Mulla *et al.*, 1992) it is wise to take all the samples at the same time of the year and to avoid critical conditions such as freezing, very wet soil and exceptionally hot and dry periods. The optimal conditions are when clods can be collected and broken apart by hand to produce a maximum of natural aggregates (they are neither too wet nor too dry). This is when farmers cultivate to prepare seed beds.

Sample should be carried to the laboratory in rigid boxes and immediately air dried. Large clods may be broken by hand as they dry when they are at the optimal moisture content. The air-dried material is then forced through a sieve of 5-mm mesh, and the 3–5-mm aggregates are selected for the tests.

Just before the treatment, aggregates are put in the oven at 40°C for 24 h so that they are at a constant matric potential. Aggregates are then ready for the three treatments.

Treatment 1: fast wetting

Immersion of aggregates in water is the simplest way to check their stability. It may be recommended as a very simple, rapid and qualitative field test. Although often criticized because it emphasizes the slaking compared to others, it appears in almost all the methods. It is a good way to compare the behaviour of a large range of soils on rapid wetting (heavy rain storms in summer).

The following treatment is proposed.

1 Five g of calibrated aggregates are gently immersed in a 250 cm^3 beaker filled with 50 cm^3 of deionized water for 10 min;

2 the water is then sucked off with a pipette;

3 the soil material is transferred to a 50-μm sieve previously immersed in ethanol for the measurement of fragment size distribution.

Treatment 2: slow wetting

Slow wetting with controlled tension corresponds to a field condition of wetting under gentle rain. It is less destructive than fast wetting and may allow a better discrimination between unstable soils. The method is as follows.

1 Five g of calibrated aggregates are put on a filter paper on a tension table at a matric potential of –0.3 kPa for 30 min (some clays and hydrophobic soils require more time to reach saturation);

2 aggregates are then transferred to a 50-μm sieve previously immersed in ethanol for the measurement of fragment size distribution.

Treatment 3: mechanical breakdown by shaking after pre-wetting

The objective of pre-wetting is to test the wet mechanical cohesion of aggregates independently of slaking. Air must therefore be removed from the aggregates before the energy is applied. This can be done either by rewetting under vacuum or by rewetting with a nonpolar liquid and then exchanging with water. Ethanol was found to be very effective (Hénin *et al.*, 1958) for this purpose.

1 Five g of calibrated aggregates are gently immersed in a 250-cm^3 beaker filled with 50 cm^3 of ethanol for 10 min;
2 the ethanol is then sucked off with a pipette;
3 the soil material is transferred in a 250-cm^3 Erlenmeyer flask filled with 50 cm^3 of deionized water; the water content is then adjusted to 200 cm^3;
4 the Erlenmeyer flask is corked and agitated end over end 20 times;
5 it is left for 30 min for sedimentation of coarse fragments;
6 excess water is then sucked off with a pipette;
7 the remaining mixture of soil and water is transferred to a 50-μm sieve previously immersed in ethanol for the measurement of fragment size distribution.

Fragment size distribution measurement

The objective of this part of the test is to measure the result of the breakdown occurring for the treatments with the minimum of additional breakdown. The measurement is divided into two operations: wet-sieving with a 50-μm sieve in ethanol, and dry-sieving of six fragment size fractions.

First, the 50-μm sieve previously immersed in ethanol which contains the soil material after the treatments is gently moved five times with a Hénin or Yoder apparatus to separate fragments <50 μm from those >50 μm. Ethanol should be used for wet sieving because it reduces additional breakdown even though large volumes of ethanol are needed. The ethanol can be recycled by filtering. If a large amount of ethanol is not available the sieving may be done in water (in this case, little additional breakdown generally occurs), but the remaining >50 μm fraction must be reimmersed in a small amount of ethanol before oven-drying and dry-sieving, to avoid recementing fragments and particles during drying.

Second, the >50 μm fraction is collected from the 50-μm sieve, oven-dried and gently dry-sieved by hand on a column of six sieves: 2000, 1000, 500, 200, 100 and 50 μm (mechanical sieving would be more difficult to control and would lead to further breakdown).

The mass percentage of each size fraction is then calculated; the fraction <50 μm is the difference between initial mass and the sum of the six other fractions. The aggregate stability for each breakdown mechanism is expressed using the resulting fragment size distribution (FSD) in seven classes or by calculating the mean weight diameter (MWD), which is the sum of the mass fraction of soil remaining on each sieve after sieving multiplied by the mean aperture of the adjacent mesh. (Calculated MWDs range between 25 μm and 3.5 mm using the set of six sieves.)

Additional treatment

Soils affected by physico–chemical dispersion generally have similar FSDs for the three treatments, with a large proportion of the material included in the <50 μm fraction. In this case a more accurate measure of disaggregation and dispersion can be obtained by measuring the clay dispersion of the suspension produced by one of the three treatments using the pipette method or turbidimetry (Pojasok & Kay, 1990; Haynes, 1993). The fast wetting, which generally gives the largest <50 μm fraction, is the most appropriate.

Interpretation of the results

The measurements made by this method can easily be compared with results of other methods such as those of Yoder or Hénin. For example, although some differences between methods exist, the equivalent of Hénin's AgE and AgA indices (percentage of soil >200 μm after water and ethanol treatments, respectively) can be calculated from the FSD of the fast wetting and wet mechanical breakdown tests. However, the new method should better discriminate between poorly aggregated materials. Also, MWD values of the three tests are directly comparable with MWD obtained by other authors (for example, Haynes, 1993) with a modified Yoder method.

Since each treatment corresponds to specific conditions in terms of initial moisture content, rate of wetting and energy applied, it is possible either to use the results of one treatment for one specific field situation or climatic condition, or to use a combination of the results of the three treatments. Although the results of the three treatments often show the same trend, different rankings of soils for the various treatments may indicate that the soils will behave differently in different climates. In addition, because of threshold effects, it is possible that only one treatment will give a good discrimination for a specific group of soils. For example, among soils containing much organic carbon, fast wetting will probably give a better separation of values than slow wetting. By contrast, the low energy slow wetting treatment will be better for distinguishing among weakly aggregated soils. For the very unstable and the very stable soils (Table 3) it was found that the three tests generally give similar MWDs, indicating that their structural behaviour is almost independent of external conditions (Amezketa *et al.*, 1996). For dispersive soils, the dispersion rate can be used as an alternative or complement to the MWD. For a simple and rapid analysis within a group of soils a single test is enough; for example, the fast wetting one.

Although summarizing results into MWD values is the easiest way to compare soils, it may be interesting to use

Table 3 Classes of stability and crustability according to MWD values measured with the three treatments offered. The differences in MWD values for the three treatments for a given soil correspond to the differences in soil behaviour which varies with initial water content and rainfall characteristics

Class	MWD value/mm	Stability	Crustability
1	< 0.4	Very unstable	Systematic crust formation
2	0.4–0.8	Unstable	Crusting frequent
3	0.8–1.3	Medium	Crusting moderate
4	1.3–2.0	Stable	Crusting rare
5	> 2.0	Very stable	No crusting

specific fraction values from the FSD for specific interpretations of the aggregate breakdown measurements. For example, a diameter of 250 μm is often considered as a limit between macro- and microaggregates with different properties (Tisdall & Oades, 1982). Furthermore, the pore size distribution within a surface crust, or the transportability of particles detached from the soil surface could be, in certain cases, inferred from the FSD. Table 3 gives an approximate classification of soils according to the MWD values. This classification can be applied for each treatment and is to be related to the climatic condition that correspond to the treatment.

The method described above was used to study the effect of a soil conditioner on the aggregate stability and crusting of silty soils (Le Bissonnais & Le Souder, 1995). It was also used in a study of the interactions between soil properties and moisture content on interrill erosion (Le Bissonnais *et al.*, 1995). For these studies the method appeared useful and efficient in the assessment of the effect of the variables studied. In addition, there was good agreement between aggregate stability measurements and crusting and erosion when these processes were measured (Amezketa *et al.*, 1996). An example of the application of this method will be presented in a subsequent paper related to the effect of organic carbon content on aggregate stability and crusting of humic soils (Le Bissonnais & Arrouays, 1997).

Conclusions

Since crusting and interrill erosion on cultivated soils result mainly from aggregate breakdown and detachment of fragments by raindrops, it seems likely that the measurement of aggregate stability with an improved method will effectively measure the soil's susceptibility to crusting and erosion. The methodological framework for measuring aggregate stability proposed takes into account the various mechanisms of aggregate breakdown, the way in which the water acts on the soil, and the soil physical and chemical properties that influence breakdown. It combines several existing methods of measuring aggregate stability into the three treatments. It is designed to compare different soils, or different climatic conditions for a given soil, not to compare time-dependent changes in that soil.

Crusting and interrill erosion, however, also depend on factors other than aggregate stability, and stability tests will never give a universal assessment of crusting and erodibility. Therefore, the objective of the tests is to provide only a basic reference for soil behaviour in specific conditions, allowing either a comparison between soils or a study of the effect of specific properties.

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