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2.6 Aggregate Stability and Size Distribution

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2.6.1 Principles

A *soil aggregate* is "a group of primary soil particles that cohere to each other more strongly than to other surrounding particles" (Soil Science Society of America, 1997). Soil aggregates can be formed by both aggregation and fragmentation processes. There are several ways of quantifying aggregate size and cohesive strength. The relative abundance of aggregates at each possible size, after breaking the soil into individual aggregates in a prescribed way, is the usual representation of the characteristic size distribution. Similarly, an abundance index may indicate stability, as the fraction of soil material that remains aggregated after a specified disruptive procedure. Other stability indices relate more directly to the force required to break an aggregate apart, usually in terms of the mechanical energy per soil mass that must be applied to achieve a certain result, such as aggregate rupture.

The analysis of soil aggregation is important in a variety of applications. Aggregate stability and size information may be used to evaluate or predict the effects of various agricultural techniques, such as tillage and organic-matter additions, and erosion by wind and water. Aggregate analysis is often used in experiments where various tillage methods are applied and then evaluated by examining the resulting stable aggregates. Because of their direct relation to cohesive forces, aggregate size and stability are important to understanding soil erosion and surface sealing. Analysis of dry aggregates may be used to estimate possible wind-erosion effects, while wet analysis may be more appropriate to evaluate or predict erosion due to rainfall impact and runoff. The stability of wet aggregates can be related to surface-seal development and field infiltration, as water-stable fractions may restrict water entry and form surface seals (Loch, 1994). Through these erosion and sealing effects, as well as the relation between aggregation and structural features such as macropores, aggregate analysis may help us understand most aspects of soil water behavior, including runoff, infiltration, and redistribution, as well as soil aeration and root growth. Increasingly, aggregate properties are being used in models that predict soil hydraulic properties, including water retention and unsaturated hydraulic conductivity (e.g., Rieu & Sposito, 1991a, b; Nimmo, 1997; Kosugi & Hopmans, 1998).

The strength of interparticle cohesion depends on a variety of soil physical, chemical, and biological influences, some of the most important being air–water surface tension, intermolecular attractive forces between water and solids, cementation by precipitated solutes, entanglement by roots and fungal hyphae, and various chemical and microbiological phenomena. In measuring aggregate size distribution or stability, we reduce the effect of these to a single function or index without distinguishing among them.

The forces applied to fragment or separate aggregates of the main bulk of soil may be similar in some ways to forces in the soil's natural setting, though they are fundamentally artificial. In the laboratory, it is impossible to exert disruptive forces that exactly oppose the microscopic forces of cohesion, so practical methods rely on the variable and unquantified forces in such processes as grinding and sieving. Some methods make use of other phenomena that break aggregates apart, especially the forces involved when water is introduced into relatively dry soil.

Measurement is complicated by the interrelationships of the variables that must be determined. The chief problem is that aggregate sizes depend on the disruptive force applied to separate them, so force and size cannot be measured independently. All practical techniques work with some combination of both. For example, size determination by sieving cannot be done without the disruptive force of collisions between the aggregates and the sieve. The concept of stability thus cannot be separated from the concept of size. Methods tend to be called *stability methods* or *size methods*, depending on which of these gets more emphasis. This difference may be in the technique itself, for example, a size method relying on a specified disruptive force or a stability method relying on the effect of force on a given size of aggregates. Alternatively, it may be in the interpretation of its results, for example, whether a measured size distribution is presented as a distribution function or as a single index (such as an average aggregate size) that is considered to indicate stability.

The forces of soil cohesion depend strongly on water content and other conditions. In a test, these conditions must be assessed or controlled. Water content is critical both because it affects the cohesive forces and also because many techniques involve deliberate wetting or immersion of the sample. Wet and dry measurements on aggregates each effectively measure different physical properties of the soil. It is not only the degree of wetness that is important, but also the means by which water has been applied. Wetting the soil in a vacuum (Kemper & Chepil, 1965; Kemper & Koch, 1966), for example, reduces the disruptive forces associated with trapped air and thus produces generally larger aggregates. Another variable is the pretreatment modifications of the soil. Some methods work with a particular size range or other subsample. Factors such as soil temperature and wetting-solution chemistry are distinct, but often minor, influences. Where they may be significant, the usual approach is to adjust lab conditions to approximate those of the field.

Ideally, the properties of aggregates would be defined on a fundamental physical basis in the way that hydraulic conductivity can be defined in terms of flux and potential gradients. If it were possible, a definition of this type would mean that any given measurement technique would provide an approximation to the defined ideal. Then as technology improves, better methods would produce results that are increasingly close approximations of the ideal. For aggregates, the definition must encompass both size and force. It is possible to define size by objectively specified geometry, but the disruptive force of the test, being mechanically complex and fundamentally dissimilar to the cohesive forces of the natural aggregate, cannot be specified in precise physical terms. Hypothetically, a fundamental definition could be formulated, for example, by designating a specific amount of disruptive force and specifying the size distribution of aggregates that results from it in terms of the radii of equivalent spheres, but the difficulty of quantifying the force prevents the use of such a definition. Research on disruptive and cohesive forces may eventually solve this problem. Le Bissonnais (1996) reviewed how several of the mechanisms routinely used to disrupt aggregates for measurement are related to conditions of measurement and to natural processes. Some experiments have measured the mechanically applied compressive force required to rupture soil aggregates. Fractal representations (described below) may also help in this effort. At present, however, we have to rely on operational definitions that endorse the result of a particular procedure with a particular apparatus and must accept that the method cannot be separated from the definition.

In specifying the procedures that effectively define the aggregate characteristics, there are three realms of variables: (i) the disrupting force or energy applied, (ii) the distribution of aggregates and particles, and (iii) the conditions of testing.

For most techniques of aggregate analysis, the disruptive procedure is standardized, but not quantified, in terms of force or energy applied. The process usually involves some combination of sieving, grinding, or application of water or other liquids. Other processes afford ways of quantifying this force or energy. One of these is the *rupture-threshold approach* of Perfect and Kay (1994). Considering one aggregate at a time, this method squeezes the aggregate between parallel plates while measuring both the applied force and the linear displacement. The integral of force as function of displacement, up to the point of rupture, is a measure of the energy applied (Perfect et al., 1998).

Another type of quantification is the *drop-shatter method* (Marshall & Quirk, 1950, Farrell et al., 1967; Díaz-Zorita et al., 2000). This procedure considers a known mass of nominally undisturbed soil, which is dropped from a known height onto a hard surface. The difference in potential energy associated with the distance of fall serves as an index of the energy applied to break apart the aggregated soil. The translation of this energy into energy promoting sample rupture is imperfect. This is partly because some of this energy goes into heat or motion rather than aggregate disruption and also because there are variations in such features as the hardness of the surface, the nature and configuration of the soil sample, and the varied modes of force transmission through the sample. Even so, it may be a useful index of the disruptive energy applied to the sample. This index relates to the energy that has been applied to the fragmented sample and does not tell what is required for a specific consequence (e.g., rupture), so it is normally used in conjunction with an abundance or distribution-based index to indicate stability.

The remainder of this section emphasizes informally standardized, operationally defined methods. For the main descriptions, we have tried to select the most widely used method for each of four properties: dry-aggregate size distribution, dry-aggregate stability, wet-aggregate size distribution, and wet-aggregate stability. We discuss more briefly alternative methods. These includes variations of the more standard methods as well as additional ones based on different principles, such as comparison of fast and slow wetting and interpretation of retention curves.

2.6.2 Apparatus and Procedures

2.6.2.1 General Sample Preparation

Sampling should be done with appropriate field-sampling equipment. A flat, square-cornered spade is recommended (Kemper & Rosenau, 1986). Samples should be taken at consistent depths if comparisons are to be made. Samples should be handled and transported in rigid containers as gently as possible to avoid compression and/or breakdown of aggregates.

Drying of aggregates before analysis should be done at room temperature or a temperature representative of field conditions. Oven-drying increases stability in otherwise unstable aggregates.

For procedures involving wet aggregates, a wetting method should be chosen based on the purpose of the analysis. Water content before sieving is a major factor in resulting stability. Fast wetting with no vacuum (Yoder, 1936) involves placing air-dried aggregates onto the sieve and immersing them in water for a period of time before beginning the mechanical sieving process. This type of wetting of dry aggregates produces disintegration and slaking (Panabokke & Quirk, 1957; Kemper et al., 1985) due to compression and expansion of entrapped air, which may be undesirable. High-vacuum fast wetting (Kemper & Chepil, 1965; Kemper & Koch, 1966) involves de-airing aggregates in a vacuum chamber under high vacuum, then instantaneously wetting the aggregates in the chamber. This method generally produces minimal disruption. Slow aerosol wetting with no vacuum (Kemper & Rosenau, 1986), in which samples on screens are wetted by vapor from below, produces little disintegration. When samples are subjected to wet sieving, stabilities are higher and more reproducible with this type of wetting, as opposed to vacuum wetting. Wetting by slow wicking with or without vacuum (Dickson et al., 1991) allows aggregates to draw moisture in from moist filter paper. Several studies have compared two or more of these wetting techniques in terms of their effect on size distribution or stability (e.g., Elliot, 1986; Haynes, 1993). Elliot found a significant difference in size distribution vs. initial water content, confirming that fast wetting caused many of the larger aggregates to break apart.

As an alternative to water in initial wetting or other procedures, organic solvents such as methanol have advantages in some cases. Organic solvents may reduce aggregate disintegration by slaking and may better preserve aggregate structure in drying (Greene-Kelly, 1973; Le Bissonnais, 1996).

2.6.2.1.a Dry-Aggregate Size Distribution

For this procedure, samples should be taken relatively dry to minimize vulnerability to disturbance. Samples should first be air-dried to constant moisture content at field humidity. A rotary sieve (Chepil, 1962; improved by Lyles et al., 1970) is desirable for consistency. Use of the same number and sizes of sieves is important in all comparable tests.

After arranging the sieves in the rotary sieving device, gently slide the air-dried sample into the feed bin and turn the device on. The duration of sieving will depend on the nature of the material and, if prolonged, may cause changes in size distributions. Weigh the size fraction caught in each sieve. If desired, repeating the procedure with the same material and weighing each size fraction again may assess changes in size distribution due to abrasion in the sieving process.

2.6.2.1.b Dry-Aggregate Stability

Chepil (1953) used the fraction of sample weight remaining after a prescribed dry-sieving operation as an index of stability. The more recent methods of Skidmore and Powers (1982) and Perfect et al. (1998) measure the energy needed to break aggregates by crushing with parallel plates, as described above in connection with quantification of the energy of rupture. The results for a significant number of aggregates need to be reduced to a statistical representation indicative of the properties of the bulk sample. For the basic index, Skidmore and Powers (1982) chose to use the energy required per increase in aggregate surface area. Perfect et al. (1998) used a distribution function that indicates the probability of failure for a given applied rupture energy, where the basic index is a parameter of the distribution formula of Weibull (1952).

2.6.2.1.c Wet-Aggregate Size Distribution

For this procedure, the sample should be taken when the soil is moist. A wet-sieving apparatus (Yoder, 1936), mechanical stirrer, and dispersing agent are required. The description of this procedure is taken from Kemper and Chepil (1965) with slight modifications:

1. Weigh 25 g of air-dried sample.
2. Prewet the sample as desired (see discussion of wetting above).
3. Spread the sample evenly on top of the nest of sieves with openings of 4.76, 2.00, 1.00, and 0.21 mm.
4. Lower the sieves into water so that the sample in the top sieve is just covered with water on the upstroke of the apparatus.
5. Raise and lower the sieves 38.1 mm through the water approximately 30 times per min for 10 min as recommended by Yoder (1936), Kemper and Chepil (1965), and Kemper and Rosenau (1986).
6. Remove the sieves from the water, oven-dry, and weigh.
7. Determine the amount of material in each fraction that is sand by rinsing and stirring the sample with a dispersing agent (such as 2 g L^{-1} sodium hexametaphosphate for soils with pH >7, or 2 g $L^{-1}$of NaOH for soils with pH <7, as recommended by Kemper & Rosenau, 1986). Alternatively, an ultrasonic probe may be used to disperse the material. After dispersing it, wash the material through the sieve again. Oven-dry any sand left in each sieve and weigh. Correct for the presence of any dispersant residue and subtract this weight from the weight of the oven-dry material from the first sieving to account for the sand fraction.

2.6.2.1.d Wet-Aggregate Stability

This procedure requires a single-sieve wet-sieving apparatus (Fig. 2.6–1) (Kemper & Koch, 1966; Kemper & Rosenau, 1986) with a 0.26-mm sieve and a

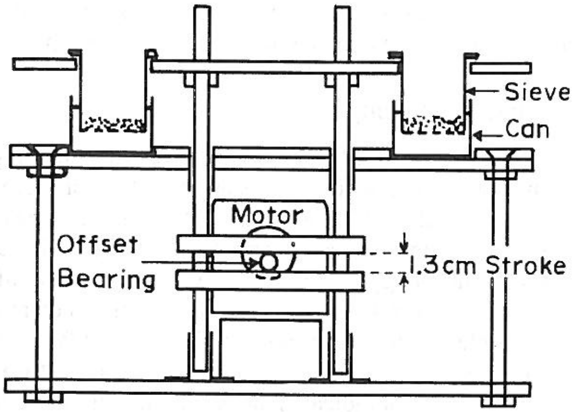

Fig. 2.6–1. Wet-sieving equipment.

dispersing agent. The description of this procedure is taken from Kemper and Rosenau (1986) with minor editorial revisions:

1. Weigh 4 g of 1- to 2-mm air-dried aggregates into numbered sieves.
2. Prewet the samples as desired.
3. Fill weighed and numbered cans with distilled water sufficient to cover the soil in the sieve on the bottom stroke of the apparatus. Place the cans into recessed holders in the apparatus.
4. Place numbered sieves containing aggregates into sieve holders so that each enters the corresponding numbered can in the sieving apparatus (see Fig. 2.6–1).
5. Start the motor and raise and lower the sieves 1.3 cm, 35 times min^{-1}, for 3 min ± 5 s.
6. Raise the sieves out of the water and place the numbered cans on a tray.
7. Replace the cans with a second numbered and weighed set containing 100 mL of dispersing solution (2 g L^{-1} sodium hexametaphosphate for soils with pH >7, or 2 g L^{-1} NaOH for soils with pH <7). Alternatively, an ultrasonic probe may be used to disperse the material.
8. Resume sieving until only sand particles are left on the sieve. If aggregates remain after 5 min of sieving, stop the apparatus and rub them across the screen with a rubber-tipped rod until they are disintegrated.
9. Continue sieving until all materials smaller than the screen opening have gone through.
10. Raise the sieves and place the numbered cans on a separate tray. These cans contain material from aggregates that were stable, except for sand particles too large to get through the screen.
11. Oven-dry both sets of cans.
12. Determine the dry weight of the material in each can. For cans with dispersing solution, subtract 0.2 g to account for the dispersing-agent weight. This correction is unnecessary if an ultrasonic probe is used instead of a chemical dispersing agent.

13. The stable fraction is equal to the weight of the soil contained in the dispersing solution cans divided by the sum of the weights in both cans.

2.6.2.2 Modifications of Informally Standardized Methods and Apparatus

Many researchers have developed modifications of sieving techniques or devices, for example, Bourget and Kemp (1957), Angers et al. (1993), Caron et al. (1992), and Chantigny et al. (1997). A typical example is that of Elliot (1986), who hand sieved with nine sieve sizes in a 3-cm motion repeated 50 times in 2 min using fast- and slow-wetted samples that had been submerged for 5 min before sieving. A more extensive development is that of Kemper and Koch (1966), who modified the Yoder (1936) apparatus to use only one screen and varied all other factors (including sieve size, sample size, prescreened aggregate size, duration of sieving time, method of wetting, and period of soaking) to optimize the reproducibility of stability measurements. The main elements of their work have been incorporated into the Kemper and Rosenau (1986) wet-stability technique described above.

Some methods use comparisons of results for equivalent soil samples that have gone through different treatments. In particular, the effects of the wetting technique and the initial water content on stability have been investigated. Amezketa et al. (1996) compared the Kemper and Rosenau (1986) wet-aggregate stability technique with a method in which the particle-size distribution of aggregates remaining on a 0.25-mm sieve was determined after each of three treatments: fast wetting, slow vapor wetting, and shaking after prewetting. This technique used ethanol instead of water to minimize further aggregate breakdown during sieving. The results may be useful for a wider range of soils than single-treatment methods.

The method of Pierson and Mulla (1989, 1990), a modification of the high-energy moisture characteristic method proposed by Childs (1940), is based on differences in the water-retention curves for fast-wetted and slow-wetted aggregates from replicate soil samples. Soil water retention is measured by the hanging-column method for thin beds of sieved aggregates on sintered glass. The wettest portion of the retention curve is considered since the matric pressure range relatively close to zero is most affected by interaggregate pores. The key principle is that the less stable the aggregates are, the more vulnerable they will be to disintegration during fast wetting, so the greater will be the difference between retention curves for the fast-wetted and slow-wetted samples. The method produces an index of aggregate stability on a dimensionless zero-to-one scale that is easily compared among different soils, but is not directly comparable with other stability indices.

Another method based on wetting processes is that of DeBoodt et al. (1961). The stability index of this method is essentially the difference in mean weight diameter between a measurement of dry-aggregate size distribution and a subsequent measurement of wet-aggregate size distribution.

North (1976, 1979) and Ahmed (1997) have used ultrasonic dispersion as a means of applying disruptive force to associate with aggregate stability. The method of North measures the quantity of large aggregates remaining after various levels of ultrasonic energy have been applied. The energy level that achieves a plateau in the quantity of aggregates remaining then serves as an index of stability. Ahmed recommended specific procedures for ultrasonic dispersion and the calculation of results as a dispersion ratio, the ratio of dispersed clay to total clay content of the sample.

Manual and visual measurements are also possible. Perfect et al. (1992) hand counted aggregates that had been sieved into six size classes. Perfect et al. (1997) chose 40 aggregates at random from each of three size classes, measured their dimensions with a caliper, and statistically correlated resulting differences in aspect ratio to soil, tillage, and size effects. Digital image-processing technology could automate this procedure.

Farres (1980) investigated how the characteristics of water-drop impacts influence aggregate breakdown. Using a single-drop rainfall simulator, drops with selected characteristics were allowed to impact single aggregates. Stability was operationally expressed as the time required for aggregate breakdown for a particular mode of application of drops. Farres found that the frequency of impacts was the most important variable in setting operating conditions, with volume of water and amount of applied energy being of secondary importance.

2.6.2.3 Representation of Data

Size-distribution methods like those of Chepil (1962) and Yoder (1936) produce a set of tabular data. For convenience in representation or for further mathematical development, these data can be fitted to a specific mathematical form.

Stability methods may produce their own stability index as a result of the specified procedures and data-analysis techniques, for example, the fraction of soil weight that comprises stable aggregates (Kemper & Rosenau, 1986), or the strength parameter(s) in Weibull's brittle fracture model (Perfect & Kay, 1994). Stability interpretations may also be derived from aggregate size distributions, usually by mathematically converting the tabular data or parameterized distribution formula to an average or other simple index. The mathematical representation of size distribution serves not only as a convenience, but also provides the link, where needed, between size distribution and stability.

To represent size distributions, the fraction of material at particular values of effective aggregate diameter can be graphed directly or cumulatively. This can be done with histograms defined by the size classifications of the measurement or with a smoothed function. Of various mathematical functions that have been used to fit the aggregate data, the lognormal distribution is one of the most useful. Being a normal (Gaussian) distribution on a log scale, this distribution is skewed toward the small-diameter end of the range covered. It also has appropriate tapering-off of abundance at both the small- and large-diameter extremes. Gardner (1956) found good lognormal fits to soils of various characteristics. The lognormal representation has also been used in some of the recent hydraulic-property models that are based on aggregate properties (e.g., Nimmo, 1997; Kosugi, 1999). As a mathematical function, the lognormal distribution is described by two parameters: the geometric mean diameter (see below) and the geometric standard deviation. In earlier times, these would be determined by manual graphing, but numerical algorithms for lognormal fits now exist in widely available software.

Fractal interpretations have been applied to both aggregate stability and size distribution (Bartoli et al., 1991; Rieu & Sposito, 1991a, b; Perfect & Kay, 1991).

A fractal characterization is valid if each subunit of the system is structurally identical (at a reduced scale) to the whole system. This idea is attractive for aggregates since they are not made of primary soil particles on an equal basis. Larger aggregates may be considered as being made of smaller aggregates that are bound internally more strongly than they are to each other.

One attribute of fractal representation is that the cumulative number–size distribution can be represented as a power law: the cumulative abundance of objects greater than a given size is proportional to that size raised to some exponent. By fractal theory, the exponent is directly related to the mass fractal dimension, so this dimension is also known once the value of the exponent is established. Geometrically, the fractal dimension depends on the shape of the objects and the extent of fragmentation. Perfect and Kay's (1991) model considers aggregates as if they were cubes, each composed of smaller cubes, so the fractal dimension depends on fragmentation alone. A greater fractal dimension means there is a greater abundance of small relative to large aggregates; in other words, the spread in sizes is more pronounced. Perfect et al. (1992) extended this work to demonstrate the practical determination of fractal parameterizations on the basis of the number distribution of aggregates. Logsdon et al. (1996) represented the density, shape, and relative diameter variables collectively with a single parameter and tested their model with sets of individually counted aggregates. The results of Logsdon et al. did not show the degree of consistency over different scales that would support the most straightforward fractal models.

Like the lognormal model, a fractal model with an appropriate fractal dimension has a distribution skewed toward the small diameters. A shortcoming of fractal models, however, is that they are fundamentally unrealistic at extremes of the range because they predict some aggregates that are smaller and some larger than any existing. Even so, fractal models remain useful for relating disruptive force to aggregate size and in general for modeling relationships between mechanical properties and other soil properties and conditions (Giménez et al., 1997; Perfect, 1997; Perfect & Blevins, 1997; Filgueira et al., 1999).

In relating aggregate size to stability, the basic idea is that bigger aggregates imply greater stability. The most widely used index for this purpose is the *mean weight diameter* (van Bavel, 1949), defined as the sum of the weighted mean diameters of all size classes, the weighting factor of each class being its proportion of the total sample weight. Ideally, this would be determined from integrating the cumulative abundance of aggregates as a function of diameter. In practice, a calculation based on the summation of size classes determined from sieving is often adequate. For example, five size classes would be known from using the apparatus of Chepil (1962). The discrete summation overestimates mean weight diameter with respect to the ideal integration of a smooth curve. Van Bavel (1949) did such an integration graphically, but modern numerical software packages facilitate this when required.

The geometric mean diameter can also serve as an aggregate size index (Mazurak, 1950), though in recent literature, it appears less often than the mean weight diameter. The natural logarithm of the geometric mean diameter is the sum of the logarithms of the weighted mean diameters of all size classes, the weighting factor of each class being its proportion of the total sample mass. The geometric mean diameter comes directly out of a lognormal fitting process, interpretable as the diameter at which one-half of the soil mass consists of smaller aggregates and one-half larger, that is, the median particle size on a weight basis.

2.6.3 Comments

Whatever method is chosen, there are additional issues to consider when using these procedures. Some of these have been discussed in detail by Kemper and Rosenau (1986) and are summarized here.

1. The stability of aggregates can increase with storage time; therefore, it is desirable to do the analysis as soon as possible following air-drying.
2. Increased salt content of the water used can also increase stability. It is desirable that the electrical conductivity of the water be <0.01 dS m^{-1}, except where low electrolyte content may lower stability, such as in sodic soils.
3. Soils with concretions (assemblages of primary particles that cannot be broken apart by the disaggregation processes of the chosen method) must be analyzed with respect to the application. In some cases, the concretions may be treated as sand because they are stable under normal cultivation practices, or in other cases, as stable aggregates because they usually have porosity, internal surface area, and exchange capacity. The relative importance of mechanical stability and internal pore structure should dictate this choice.

Some soils may be nearly 100% stable by the wet-stability method of Kemper and Rosenau (1986). This commonly occurs with soils from humid regions. Kemper and Rosenau (1986) recommend the use of greater disruptive force, achievable through such means as increasing the duration and amplitude of sieving or by selecting a more disruptive wetting technique. This enables the detection of differences among highly stable soils, although at the expense of precluding the possibility of comparing results with those obtained by more standard procedures on less stable soils. On the general problem of working with soils whose aggregate stability is at an extreme of the range of applicability of a given method, Le Bissonnais (1996) recommends that a combination of methods be applied so that comparisons are more likely to be possible even among diverse soils.

The application of aggregate size and stability information requires the choice of a method and defined property that cannot be separated from each other. One can focus on either stability or size distribution, and on either wet or dry aggregates. The needs of the application should guide this selection. Erosion applications, for example, usually relate more directly to stability, while hydraulic and gas-transport properties may relate more directly to the size distribution. The choice of wet or dry aggregates for measuring may depend on which condition most resembles the field situation, or on such considerations as reproducibility or consistency with other measurements.

The choice between widely used, informally standardized methods and more novel ones often involves a substantial tradeoff between the need for consistency and the ultimate appropriateness of the method. The more standardized methods facilitate comparability, but the quantitative indices they generate may not give the sort of aggregate characterization most pertinent to the application at hand. Another drawback to the reliance on operational definitions is that it makes it awkward to incorporate ongoing scientific advances into conceptualizations and techniques. To incorporate such improvements, an established definition can be changed by consensus of the scientific community, but these changes lead to incompatibility in comparisons with earlier results. Research that leads to standardization of the specified force and a fundamental physical definition would help in allowing aggregate-measurement technology to advance without a loss of comparability.

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