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Macro- and micro-aggregate stability of soils determined by a combination of wet-sieving and laser-ray diffraction

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Abstract

Soil structural stability affects the profitability and sustainability of agricultural systems. Different-sized structural units have different stability mechanisms and respond differently to such external factors as rain, wind, irrigation and management. A comprehensive analysis of the soils structural stability requires its characterization at the macro- and micro-aggregate scales. We determined the aggregate stability of 36 soils at the macro-aggregate scale using wet-sieving methods and of 20 soils at the micro-aggregate scale using laser-ray diffraction techniques. All the tests gave consistent estimates of aggregate stability. Most soils were homogeneous and quite stable at the macro-aggregate level as determined by the «water stable aggregate» parameter, but differed significantly among them and were quite unstable at the micro-aggregate level as determined by the «mean weight diameter of micro-aggregates» parameter. Slaking induced by the fast wetting of aggregates was the main destabilizing mechanism in these soils (88% of the soils had slaking stability index values < 0.5), whereas most soils were quite tolerant to the mechanical shaking of aggregates (89% of the soils had stirring stability index values > 0.5). The combination of the macro- and micro-aggregate stability tests is a consistent way for describing the structural stability of the studied soils.

Key words: soil structural stability, wetting, stirring, aggregate-breakdown, slaking stability index, stirring stability index.

Resumen

Determinación de la estabilidad de macro- y micro-agregados del suelo mediante una combinación de técnicas de tamizado en húmedo y difracción de rayos láser

La estabilidad estructural del suelo afecta a la rentabilidad y sostenibilidad de los agrosistemas. Los agregados de distintos tamaños son estabilizados por mecanismos diferentes, y responden de forma diferente frente a la lluvia, el viento, el riego y otras prácticas agronómicas. Un análisis completo de la estabilidad estructural de los suelos requiere su caracterización a nivel de macro- y micro-agregados. En este trabajo se ha determinado la estabilidad de macroagregados de 36 suelos mediante métodos de tamizado en húmedo, y la estabilidad de microagregados de 20 suelos mediante técnicas de difracción de rayos láser. Todos los ensayos estimaron de forma consistente la estabilidad de agregados. La mayoría de los suelos se comportaron homogéneamente y de forma bastante estable al nivel de macroagregados, de acuerdo con los valores del parámetro «agregados estables en agua», mientras que se comportaron de forma muy diferente y muy inestable al nivel de microagregados, de acuerdo a los valores del parámetro «diámetro medio ponderado de los microagregados». La desagregación inducida por la humectación rápida de los agregados (*slaking*) fue el mecanismo más desestabilizador en estos suelos (el 88% de los suelos presentó índices de estabilidad frente a *slaking* $< 0{,}5$), mientras que la mayoría de los suelos fueron bastante estables frente a la agitación mecánica de los agregados (el 89% de los suelos presentó índices de estabilidad frente a la agitación $> 0{,}5$). La combinación de pruebas de estabilidad de macro- y micro-agregados es un procedimiento consistente y necesario para entender la estabilidad estructural de los suelos estudiados.

Palabras clave: estabilidad estructural de suelos, humectación, agitación, desagregación, índice de estabilidad frente a *slaking*, índice de estabilidad frente a agitación.

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Introduction

Soil aggregate stability, defined as the ability of the aggregates to remain intact when subject to a given stress, is an important soil property that affects the movement and storage of water, aeration, erosion, biological activity and the growth of crops. Tisdall and Oades (1982) categorized soil aggregates by size into three main hierarchical levels: clay-aggregate (< 2 mm), micro-aggregate (2-250 mm), and macro-aggregate (> 250 mm) units. These differential-sized structural units are stabilized by diverse mechanisms and behave differently against external stresses such as rain, wind, irrigation and other cultural practices. Consequently, a complete characterization of the structural stability of soils requires an analysis of aggregate stability at both macro- and micro-scales.

Macro-aggregate stability may be quantified by means of the parameter «water stable aggregates» (WSA) defined as the percentage of total aggregates that remain stable (aggregates > 250 µm) following slow-wetting and shaking and chemical actions. WSA is obtained through a simple, fast and reproducible wet-sieving test proposed by Kemper and Koch (1966) and improved by Kemper and Rosenau (1986). Macro-aggregate stability may also be quantified by means of the parameter «mean weight diameter» (MWD) of the aggregates remaining stable after their exposure to three treatments (fast wetting, slow wetting and stirring after prewetting) plus a subsequent wet sieving in ethanol (Le Bissonnais, 1988). This method, later modified by Amézketa *et al.* (1996), is more laborious and complex than the standard Kemper and Rosenau test, but characterizes better some of the basic mechanisms of aggregate breakdown. Thus, fast wetting MWD (MWD_{fast}) measures the stability of aggregates subject to the compression of the entrapped air within the aggregates (slaking of aggregates), slow wetting MWD (MWD_{slow}) measures the stability of aggregates subject to differential swelling (microcracking of aggregates), and stirring after prewetting MWD (MWD_{stir}) measures the stability of aggregates subject to mechanical shaking (wet mechanical cohesion of aggregates) (Le Bissonnais, 1996).

Micro-aggregate stability may be quantified by measuring clay-size particles (≤ 2 mm diameter) (van Olphen, 1977), specific silt-size particles (≤ 5 and/or ≤ 20 mm) (Abu-Sharar *et al.*, 1987), or specific sand-size particles (≤ 125 mm) (Loch and Foley, 1994), although it is best quantified by analysing the overall size distribution of the fragments that result from the breakdown of aggregates in the macro-aggregate tests (Le Bissonnais *et al.*, 1989; Chan and Mullins, 1994; Le Bissonnais, 1996). Pojasok and Kay (1990) measured the dispersible clay in the same soil sample where WSA was determined in order to save time and perform both measurements at the same energy input level. Fragment size distribution and micro-aggregation may be easily quantified by laser-ray diffraction (Cooper *et al.*, 1984; Buurman *et al.*, 1997). This technique was used by Muggler *et al.* (1997) to study aggregation in Brazilian Oxisols, and by Westerhof *et al.* (1999) to determine the changes in grain size distribution of these soils upon stirring and wetting.

We used these macro- and micro-aggregate stability tests with the objectives of (1) quantifying and ranking the structural stability of the studied soils and (2) determining the relative importance of some of the destabilizing processes in these soils.

Material and Methods

We studied 36 soils from two important irrigated areas (Bardenas and Monegros) of the middle Ebro river basin (Spain). These soils were variable in their taxonomic classification (Soil Survey Staff, 1999), cropping history and chemical and physical properties (Table 1). The soil samples were taken at 0-20 cm depth (6 soils were also sampled at deeper depths), air-dried and stored. Chemical and physical soil properties were analysed by standard methods (Carter, 1993). X-ray diffraction patterns of the clay fraction showed them to be rich in hydrated micas (>70% of total clay) and chlorites (5-20% of total clay), very low in kaolinite and pyrophyllite (< 5% of total clay) and absent in swelling smectites and vermiculites.

The macro-aggregate stability of these soils was measured in four-replicated 1-2 mm aggregates using the wet-sieving tests developed by Kemper and Rosenau (1986) and Le Bissonnais (1988) (modified by Amézketa *et al.*, 1996). The methodology of these tests was given in Amézketa *et al.* (1996). The stability parameters obtained were the previously defined WSA and MWD. Figure 1 shows a schematic diagram of the macro-aggregate stability tests.

The micro-aggregate stability was quantified in 20 soils by determining through laser-ray diffraction techniques (Coulter LS230 laser grain-sizer with a 5-mW, 750 nm laser beam of 0.04 to 2,000 µm

Table 1. Taxonomic classification and physical and chemical properties of the 36 studied soils

Soils	Classification	Soil saturation extract				Soil texture[&]			Water content at		Total OM %	Equivalent $CaCO_3$ %	CEC cmol kg^{-1}	CBD-extractable*		
		ECe	SARe	SARe/ECe	pHe	Sand	Silt	Clay	0.03 MPa	1.5 MPa				Mn	Fe	Al
		dS m^{-1}	$(mmol\ L^{-1})^{0.5}$					g kg^{-1}							g kg^{-1}	
Bardenas I																
SA 2/E7[a]	Typic xerorthent	1.0	1.3	1.3	8.4	342	381	277	249	100	2.6	39.8	16.8			
EC 2/E8[a]	Typic xerofluvent	0.9	1.6	1.8	8.5	46	467	487	270	100	2.8	32.9	15.7			
SA 3/1[a]	Petrocalcic xerochrept	0.5	0.2	0.4	8.1	383	280	338	267	153	2.1	30.6	19.0	0.3	11.8	1.2
SA 13/1[a]	Typic xerorthent	1.4	4.2	3.0	9.0	388	345	267	226	131	1.4	36.6	12.9	0.2	8.2	0.7
SA 16/1[a]	Calcixerollic xerochrept	0.6	0.4	0.7	8.5	415	249	336	245	144	2	28.0	22.7	0.4	12.0	1.1
SA 20/1[a]	Gypsic xerochrept	0.9	2.3	2.5	8.8	286	500	214	221	108	1.1	42.2	22.0	0.2	6.6	0.5
SA 20/5[a]	Gypsic xerochrept	3.6	3.0	0.8	8.1	173	462	365	254	153	1	31.3	23.2			
SA 21/1[a]	Calcixerollic xerochrept	0.6	0.7	1.2	8.7	519	260	222	210	119	1.6	38.5	22.7	0.2	7.9	0.7
SA 26/2[a]	Gypsic xerochrept	9.7	9.0	0.9	7.8	224	494	282	255	155	1.8	39.7	14.2			
SA 27/2[a]	Gypsic xerochrept	0.8	0.8	1.0	8.4	32	480	489	266	187	1.6	32.4	24.0			
SA 30/5[a]	Typic xerofluvent	1.2	4.1	3.4	8.8	267	525	209	239	139	2.2	38.5	16.4			
SA 31/1[a]	Typic xerofluvent	16.1	23.6	1.5	8.0	214	502	284	234	147	1.6	44.0	21.6			
SA 37/1		1.3	1.1	0.9	8.4	377	374	249	227	135		36.8	16.0			
SA 42/1		12.6	14.5	1.2	8.1	30	588	382	311	197		35.7	4.5	0.3	12.1	1.0
SA 44/1		4.9	9.2	1.9	8.2	142	507	352	268	162		34.9	20.4	0.4	10.1	1.1
SA 49/1		10.9	17.5	1.6	8.1	50	617	333	268	150		40.2	13.4			
SA 60/1		1.0	1.1	1.1	8.5	234	513	253	243	140		38.4	13.0			
SA 63/1		2.2	2.1	1.0	8.3	246	435	319	230	146		40.6	19.0			
SA 81/1		2.9	2.9	1.0	8.3	66	486	448	327	210		23.8	24.7	0.4	12.3	1.1
SA 92/1		1.1	0.9	0.9	8.5	315	486	200	210	94		39.6	12.1	1.6	7.1	5.3
Monegros I																
Callen 1[a]	Typic xerofluvent	19.2	111.4	5.8	9.1	453	362	186			1.5	21.4	11.8	0.3	11.7	0.9
Tramaced 2[a]	Typic natrixeralf	4.2	5.6	1.3		82	543	375			3.1	20.6	17.6	0.4	18.2	1.3
Sariñena 4[a]	Xeric petrocalcid	0.8	0.3	0.4		316	364	320			4.1	12.1	26.0	0.5	19.0	1.8
Violada 10[a]	Gypsic haploxerept	3.2	0.2	0.1		176	519	305			4.6	35.5	21.3			
SJF 8[a]		3.5	1.7	0.5		342	399	259			3.2	31.0	13.2			
Fraella 1[a]	Typic natrixeralf	0.7	1.3	1.9		261	524	215	278	82	2.1	22.1	8.3			
Fraella 2[a]	Typic natrixeralf	6.3	136.2	21.6		1	456	543	410	174	0.6	18.7	12.0			
Flumen[a]	Typic xerofluvent	59.3	73.9	1.3		341	495	164	231	68	0.8	27.4	5.0			
Valfonda 1	Gypsic haploxerept	7.1	7.7	1.1	7.6	514	579	369	330	212	1.6	30.4	17.7			
Montesusin 1B	Typic xerofluvent	2.8	3.0	1.1		92	531	377	287	181	2.4	28.6	7.1			
Barbués 2/1	Typic xerofluvent	1.3	3.9	2.9	7.8	291	518	191	244	108	1.7	23.4	8.8	0.2	9.8	0.6
Barbués 3/1	Xeric torriorthent	6.2	13.6	2.2	8.0	300	526	174	222	115	1.4	25.8	5.2	0.1	9.9	8.6
Barbués 3/2	Xeric torriorthent	4.1	15.7	3.9	8.3	171	524	305	220	127	0.7	29.0	9.5			
Grañén T1	Typic xerofluvent	1.8	0.8	0.4	8.3	153	467	380	246	163	2.3	29.6	15.4	0.3	11.5	0.9
Grañén T2	Typic calcixerept	0.8	0.4	0.5	8.4	550	195	255	179	106	3	25.6	10.4	0.3	9.6	0.7
Grañén 1	Typic xerofluvent	3.4	7.1	2.1	8.0	299	569	132	257	113	2.5	24.5	16.9	0.3	13.2	0.9

[a] Samples in which micro-aggregate stability was quantified using laser-ray diffraction technique. [&] Soil texture: sand (50-2,000 µm); silt (2-50 µm); clay (< 2 µm) . * CBD extractable Mn, Fe and Al: citrate-bicarbonate-dithionite-extractable Mn, Fe and Al.

range), the fragment size distribution ($FSD_{microag}$, in % volume) in each of the four-replicated suspensions (fragments < 250 µm in diameter) obtained in the macro-aggregate breakdown of the Kemper and Rosenau test (Figure 1). The fragments were grouped in six classes (0.04-2, 2-5, 5-20, 20-50, 50-100, and 100-250 µm). The suspensions with densities higher than those given by the instrument's specifications were diluted with tap water following Buurman *et al.* (1997). The calculation model uses Fraunhofer, the «polarization intensity differential of scattered light» (PIDS) and Mie theory. For the calculation model, we used tap water as medium (refractive index = 1.33 at 20ºC), and a refractive index of 1.5 for the solid phase.

The $FSD_{microag}$ values were integrated for each soil by means of the «mean weight diameter of micro-aggregates» ($MWD_{microag}$), calculated as the sum of the soil mass fractions of each class multiplied by the mean size of each class. The reproducibility of the FSD measured with the Coulter LS230 on the same soil sample suspension was very high (coefficient of variation, CV≈1-2%). The stirring time for a complete FSD characterization was 90 seconds. We measured the percent of fragments < 5 µm after various increasing stirring times and found that it increased only by 2-4% at a maximum stirring time of 450 seconds. Disaggregation during the time of measurement was therefore negligible, so that the measured FSD was exclusively the result of macro-aggregate breakdown.

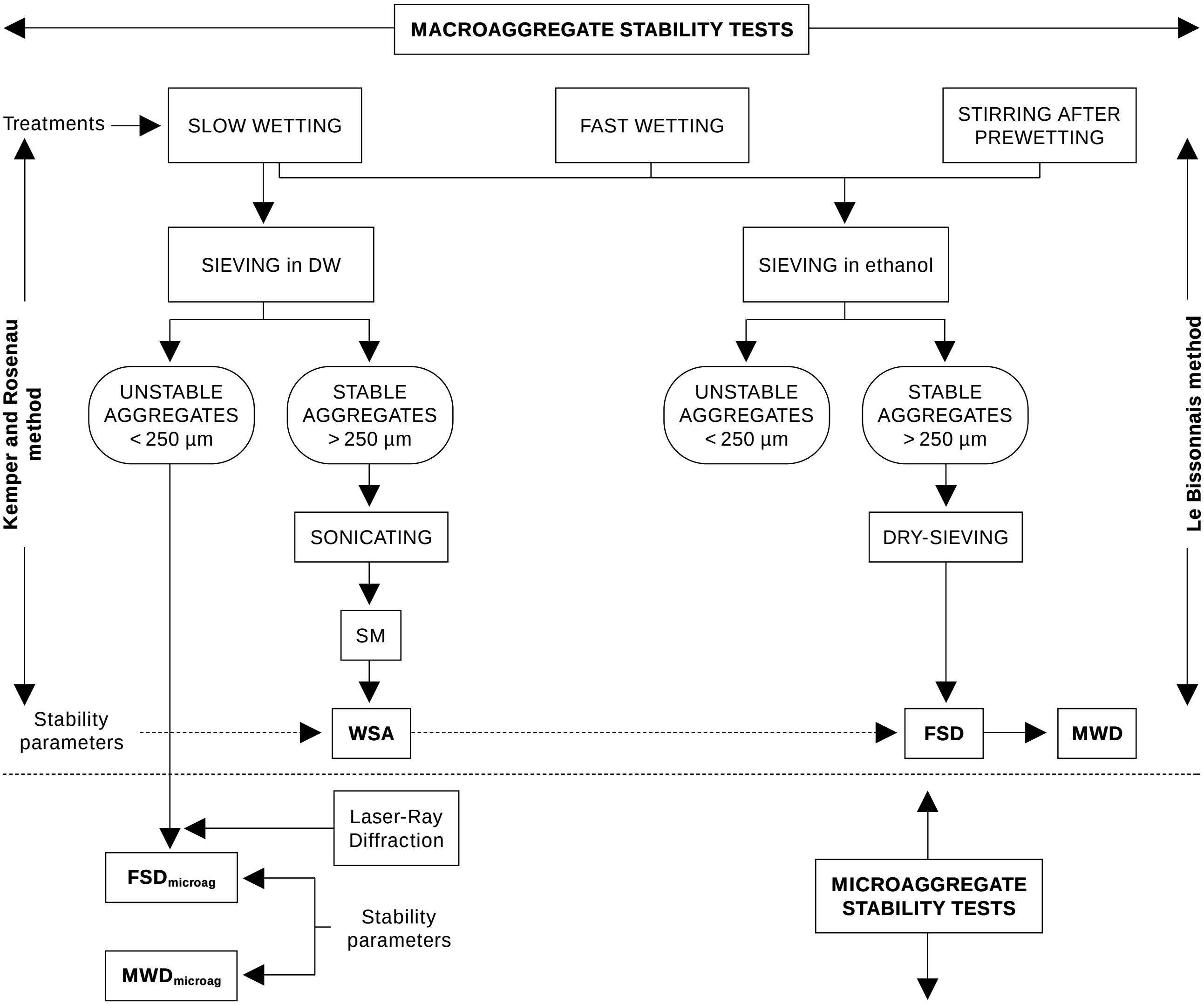

Figure 1. Schematic diagram of the macro- and micro-aggregate stability test. DW: deionized water. SM: sand mass. WSA: water stable aggregates. FSD: fragment size distribution. MWD: mean weight diameter.

The fragment size distribution resulting from macro-aggregate breakdown in the Le Bissonnais method was not quantified because (i) the broken fragments in this method were immersed in ethanol, and (ii) it was not possible to use the coulter with large proportions of this organic liquid.

Statistical analyses were performed using the Statgraph *Plus* 2.1 software. One-way ANOVA was carried out to compare the means of the stability parameters among soils. When ANOVA showed significant differences at $P \leq 0.05$, the Duncan's multiple range test was used to classify the soils in homogeneous groups. A non-parametric statistical test (Spearman rank correlation test) was also applied. The non-parametric statistical Spearman correlation is based on the ranks of the data rather than the data itself, so that it is resistant to outliers. Statistical significance was reported at the 0.05 (*), 0.01 (**) and 0.001 (***) probability levels.

Results

Soil macro-aggregate stability

The results obtained in the macro-aggregate stability tests were precise and reproducible. Thus, 92% of the CV's of the mean WSA values obtained in the Kemper and Rosenau test and 85% of the CV's of the mean MWD values obtained in the Le Bissonnais test for the four replicated soil suspensions were lower than 10%, and the average CV of the WSA and the MWD parameters were 5.1% and 6.2%, respectively.

The average WSA for the 36 soils was 84%, and ranged between 57% (Fraella 2) and 98% (SA 16/1) (Table 2). The low CV (12%) of the mean WSA suggests that this parameter did not properly discriminate for the differential stability among soils shown later in other tests. Thus, the Duncan test established 5 different homogeneous groups of soils on the basis of their WSA values, but 28 soils were in the same group (Table 2).

The results obtained for the 36 soils in the macro-aggregate stability test of Le Bissonnais were evaluated through the MWD values obtained in the 3 treatments (slow wetting: MWD_{slow}; fast wetting: MWD_{fast}; and stirring after prewetting: MWD_{stir}). Since soil stability decreases as MWD decreases, the results shown in Table 3 indicate that macro-aggregate stability decreased in the order: slow wetting (average $MWD_{slow} = 1.29$ mm) > stirring after prewetting (average $MWD_{stir} = 0.83$ mm) > fast wetting (average $MWD_{fast} = 0.41$ mm).

Table 2. Macro-aggregate stability (Kemper and Rosenau) test: mean water stable aggregate (WSA) values of the 36 studied soils. Soils ranked from low to high WSA. Soils with «×» within the same column are not significantly different ($P > 0.05$)

Soil	WSA (%)	Homogeneous groups
Fraella 2	56.5	×
Flumen	62.9	××
SA 31/1	64.6	×××
Grañén 1	70.4	××××
Barbues 3/2	70.6	×××××
Grañén T1	73.1	×××××
SA 63/1	75.0	×××××
Tramaced 2	75.3	×××××
SA 49/1	76.1	×××××
Barbués 3/1	76.6	×××××
Valfonda 1	78.2	×××××
Montesusin 1B	81.3	×××××
SA 44/1	82.6	×××××
Callen 1	83.4	×××××
SA 60/1	83.6	×××××
SA 92/1	85.0	×××××
SA 42/1	85.2	×××××
SA 20/1	86.2	×××××
SA 2/E7	88.0	×××××
SA 13/1	88.3	×××××
Violada 10	88.9	×××××
SA 21/1	89.2	×××××
SA 30/5	89.4	×××××
Sariñena 4	90.2	×××××
Grañén T2	90.5	×××××
SA 81/1	90.9	×××××
SJF 8	91.1	×××××
Barbués 2/1	92.1	×××××
EC 2/E8	92.9	×××××
SA 37/1	94.5	×××××
SA 20/5	94.9	×××××
Fraella 1	95.1	×××××
SA 26/2	95.6	××××
SA 3/1	96.3	×××
SA 27/2	96.3	××
SA 16/1	97.6	×

MWD_{slow} varied between 1.05 (Grañén T1) and 1.43 mm (SA 26/2), and the CV of the mean MWD_{slow} was low (7%). Even though 5 homogeneous groups were found on the basis of the MWD_{slow} values, 28 out of the 36 soils were in the same group, indicating that most studied soils behaved similarly and were relatively stable from the point of view of microcracking of aggregates. Based on the MWD_{slow} values, SA 26/2 and Grañen T1 will be the most stable and unstable soils, respectively.

Table 3. Macro-aggregate stability (Le Bissonnais) test: mean weight diameter (MWD) values of the 36 studied soils obtained in the slow, fast and stirring treatments. For each parameter, the soils are ranked from low to high values. Soils with «×» within the same column are not significantly different (P > 0.05)

Soil	MWD_{slow} (mm)	Homogen.* groups	Soil	MWD_{fast} (mm)	Homogen.* groups	Soil	MWD_{stir} (mm)	Homogen.* groups
Grañén T1	1.05	×	SA 60/1	0.21	×	SA 92/1	0.31	×
Barbués 3/1	1.08	××	SA 44/1	0.24	××	Fraella 2	0.52	×
SA 92/1	1.12	×××	SA 42/1	0.24	×××	Flumen	0.60	××
Barbués 3/2	1.16	××××	EC 2/E8	0.27	×××	Callen 1	0.61	××
SA 44/1	1.19	×××××	SA 27/2	0.29	×××	SA 49/1	0.63	××
Grañén 1	1.20	×××××	SA 92/1	0.29	×××	SA 44/1	0.68	××
SA 49/1	1.23	×××××	SA 20/5	0.30	×××	SA 63/1	0.69	××
Montesusin 1B	1.24	×××××	Montesusin 1B	0.30	×××	Grañén T1	0.69	××
Callen 1	1.25	×××××	SA 63/1	0.30	×××	Barbués 3/2	0.72	××
Tramaced 2	1.25	×××××	Grañén T1	0.31	×××	SA 60/1	0.75	××
Barbués 2/1	1.26	×××××	Violada 10	0.33	×××	SA 20/1	0.76	××
SA 31/1	1.26	×××××	Tramaced 2	0.33	×××	SA 16/1	0.77	××
Grañén T2	1.26	×××××	SA 20/1	0.33	×××	Tramaced 2	0.78	××
SA 2/E7	1.29	×××××	SA 37/1	0.34	×××	Valfonda 1	0.80	××
Valfonda 1	1.30	×××××	SA 13/1	0.35	×××	SA 13/1	0.82	××
SA 60/1	1.30	×××××	SA 16/1	0.35	×××	Montesusin 1B	0.83	××
SA 63/1	1.30	×××××	Grañén 1	0.36	×××	SA 31/1	0.84	××
Flumen	1.31	×××××	Callen 1	0.40	×××	SA 2/E7	0.85	××
SA 42/1	1.31	×××××	SA 30/5	0.41	×××	EC 2/E8	0.85	××
SA 30/5	1.31	×××××	SA 81/1	0.42	×××	SA 37/1	0.87	××
Violada 10	1.32	×××××	SJF 8	0.42	×××	Grañén T2	0.89	××
Fraella 2	1.32	×××××	SA 49/1	0.42	×××	Barbués 2/1	0.90	××
SA 37/1	1.34	×××××	SA 2/E7	0.43	×××	Violada 10	0.90	××
SA 81/1	1.35	×××××	Sariñena 4	0.44	×××	SA 21/1	0.92	××
SJF 8	1.35	×××××	SA 26/2	0.45	×××	SJF 8	0.93	××
SA 27/2	1.35	×××××	SA 31/1	0.46	×××	Barbués 3/1	0.93	××
Sariñena 4	1.35	×××××	SA 3/1	0.5	×××	Grañén 1	0.94	××
SA 13/1	1.35	×××××	Flumen	0.52	×××	SA 30/5	0.95	××
SA 20/1	1.36	×××××	Barbués 3/2	0.53	×××	SA 81/1	0.95	××
SA 21/1	1.36	×××××	Barbués 2/1	0.54	×××	SA 3/1	0.96	××
EC 2/E8	1.37	×××××	Barbués 3/1	0.61	×××	SA 42/1	0.96	××
SA 20/5	1.39	×××××	Grañén T2	0.63	×××	SA 20/5	0.96	××
Fraella 1	1.39	××××	SA 21/1	0.63	××	Sariñena 4	0.97	××
SA 16/1	1.40	×××	Valfonda 1	0.70	×	SA 27/2	1.01	×
SA 3/1	1.42	××	Fraella 2	**		SA 26/2	1.13	×
SA 26/2	1.43	×	Fraella 1	0.87	×	Fraella 1	1.26	×

* Homogen.: homogeneous groups. ** Anomalous value (not included).

MWD_{fast} varied between 0.21 (SA 60/1) and 0.87 mm (Fraella 1), although most soils had values lower than 0.5 mm, indicating that their aggregates readily slaked when subject to fast wetting. The high CV (35%) of the mean MWD_{fast} reflects the differential behaviour of these soils against fast wetting. The Duncan test showed significant differences among our studied soils, grouping them in 4 stability classes, although 30 of them were in the same group. Based on the MWD_{fast} values, Fraella-1 and SA 60/1 will be, respectively, the most stable and unstable soils to slaking.

MWD_{stir} varied between 0.31 mm (SA 92/1) and 1.26 mm (Fraella 1), with a CV of the mean of 21%. The Duncan test showed significant differences among soils, grouping them in 5 groups (although 31 were in the same group). Based on this parameter, Fraella 1 will be the most stable soil, followed by SA 26/2 and SA 27/2, whereas SA 92/1 and Fraella 2 will be the most unstable soils to mechanical shaking.

Based on the MWD values shown in Table 3, we calculated two macro-aggregate stability indexes related to slaking and stirring (Table 4). The «slaking stability index» ($SI_{slaking}$), calculated as

$$SI_{slaking} = \frac{MWD_{fast}}{MWD_{slow}} ,$$

quantifies the decreases in stability caused by the slaking of aggregates in the fast wetting treatment as compared to the lack of slaking in the slow wetting treatment. This index varies between 1 and 0, and high values indicate that aggregates subject to the fast wetting treatment exhibit minor slaking.

Table 4. Macro-aggregate stability (Le Bissonnais) test: slaking stability index ($SI_{slaking}$) and stirring stability index ($SI_{stirring}$) values of the 36 studied soils

Soil	$SI_{slaking}$	$SI_{stirring}$
SA 2/E7	0.33	0.66
EC 2/E8	0.20	0.62
SA 3/1	0.35	0.68
SA 13/1	0.26	0.61
SA 16/1	0.25	0.55
SA 20/1	0.24	0.56
SA 20/5	0.22	0.69
SA 21/1	0.46	0.68
SA 26/2	0.31	0.79
SA 27/2	0.21	0.75
SA 30/5	0.31	0.73
SA 31/1	0.37	0.67
SA 37/1	0.25	0.65
SA 42/1	0.19	0.73
SA 44/1	0.20	0.57
SA 49/1	0.34	0.51
SA 60/1	0.16	0.58
SA 63/1	0.23	0.53
SA 81/1	0.31	0.70
SA 92/1	0.26	0.28
Callen 1	0.32	0.49
Tramaced 2	0.26	0.62
Sariñena 4	0.33	0.72
Violada 10	0.25	0.68
SJF 8	0.31	0.69
Fraella 1	0.63	0.91
Fraella 2	*	0.39
Flumen	0.40	0.46
Valfonda 1	0.54	0.62
Montesusin 1B	0.24	0.67
Barbués 2/1	0.43	0.71
Barbués 3/1	0.56	0.86
Barbués 3/2	0.46	0.62
Grañén T1	0.30	0.66
Grañén T2	0.50	0.71
Grañén 1	0.30	0.78

* Anomalous value (not included).

The «stirring stability index» ($SI_{stirring}$), calculated as

$$SI_{stirring} = \frac{MWD_{stir}}{MWD_{slow}} ,$$

quantifies the decreases in stability caused by the reduction of the wet mechanical cohesion of aggregates (slaking and swelling of aggregates is prevented in the stirring treatment due to the ethanol prewetting, so that only the wet mechanical cohesion of aggregates is measured; Le Bissonnais, 1996). This index varies between 1 and 0, and high values indicate that aggregates subject to the stirring treatment exhibit a high wet mechanical cohesion.

The low $SI_{slaking}$ values given in Table 4 indicate that most of the soils were very susceptible to slaking. Thus, the average $SI_{slaking}$ was 0.32, 88% of the 36 soils had $SI_{slaking} < 0.5$ and 4 of them (SA 60/1, SA 42/1, EC 2/E8 and SA 44/1) had $SI_{slaking} \leq 0.2$, so that they will be highly susceptible to the mechanical breakdown of aggregates caused by fast wetting.

On the other hand, the relatively high $SI_{stirring}$ values given in Table 4 indicate that the wet mechanical cohesion was generally high enough to maintain soil aggregation. Thus, the average $SI_{stirring}$ was 0.64 and only 11% of the 36 soils had $SI_{stirring} < 0.5$ (SA 92/1, Fraella 2, Flumen and Callen 1 soils), so that only these soils will be susceptible to the mechanical breakdown caused by the impact energy of water drops.

Soil micro-aggregate stability

The results obtained in the micro-aggregate stability test were not as consistent as those obtained in the macro-aggregate stability tests, since the average CV of all the size classes and soils was 17%, with only 53% of the CV's of the mean percentage of each size fraction calculated from the four-replicated suspensions being lower than 10%. However, the highest CV's were obtained for the largest fragments (> 50 µm) due to its very low quantity, so that this apparent variability was not relevant in practical terms. In fact, the reproducibility of the test for fragments smaller than 50 µm was high, as indicated by their CV's that were lower than 10%, and by the average CV of 9.3% for the $FSD_{<50\mu m}$ parameter.

The breakdown of macro-aggregates in the standard test (Kemper and Rosenau, 1986) produced different micro-aggregate sizes, as shown by their frag-

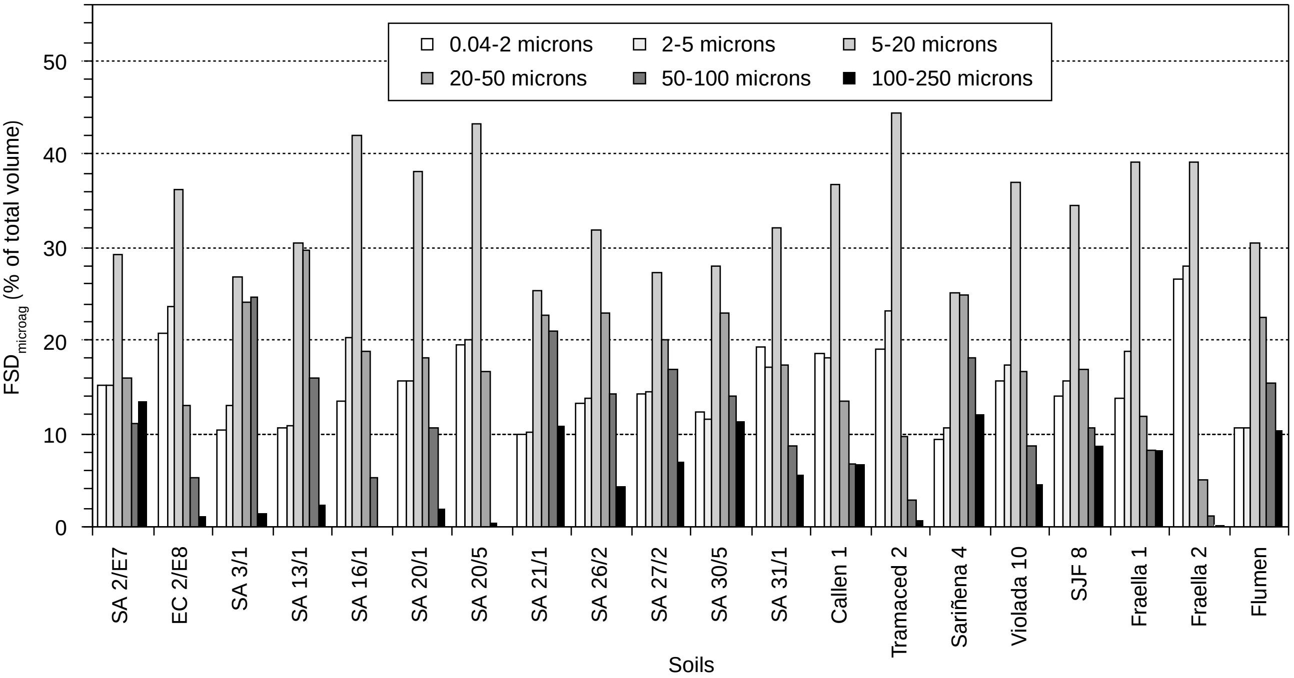

Figure 2. Fragment size distribution of microaggregates ($FSD_{microag}$) resulting from the macro-aggregate breakdown in the Kemper & Rosenau test for the 20 studied soils. Each bar is the mean of four replications.

ment size distribution values ($FSD_{microag}$) (Fig. 2). These fragments were generally small, the highest proportion being between 5 and 20 μm, whereas the low proportion of fragments <2 μm indicate that clay dispersion was not important in general. Significant differences were observed among soils' $FSD_{microag}$, as illustrated in Table 5, where the $FSD_{microag}$ values were grouped into two size-classes (< 20 μm and > 20 μm).

The $FSD_{microag}$ values were integrated for each soil by means of the parameter $MWD_{microag}$. The theoretical variation interval of the $MWD_{microag}$ is between 1 and 175 μm. The average $MWD_{microag}$ for the 20 soils was 29.3 μm (CV = 39%), with a variation interval between 9.1 and 47.1 μm (Table 5), indicating that the studied soils were in general quite unstable from the micro-aggregate point of view. The high CV of the mean is a consequence of the differential behaviour of soils. Thus, the Duncan test ranked them into 8 homogeneous groups (Table 5). Since soil's susceptibility to crusting increases as the $MWD_{microag}$ decreases, we concluded that Sariñena 4 and SA 21/1 ($MWD_{microag}$ > 46 μm) were most tolerant, and Fraella 2, SA 20/5, Tramaced 2, EC 2/E8 and SA 16/1 ($MWD_{microag}$ < 17 μm) most susceptible, respectively, to crusting.

Comparison among soil-aggregate stability parameters

The values of standardized skewness and standardized kurtosis indicate that the macro-aggregate stability parameters departed from normality, therefore preventing the use of linear regression techniques. We therefore compared the ranking in soil's structural stability established by the nine parameters determined in this work (WSA, MWD_{slow}, MWD_{fast}, MWD_{stir}, $SI_{slaking}$, $SI_{stirring}$, $MWD_{microag}$, $FSD_{microag<20\mu m}$ and $FSD_{microag>20\mu m}$) by means of the Spearman rank correlation (r_s) test, which does not require normality (Table 6).

WSA ranked the soils in a similar order than MWD_{slow} ($r_s = 0.72^{***}$), MWD_{stir} ($r_s = 0.65^{***}$) and $SI_{stirring}$ ($r_s = 0.43^{**}$), and in a different order than MWD_{fast} ($r_s = 0.03^{NS}$) and $SI_{slaking}$ ($r_s = -0.11^{NS}$). This is an expected and consistent result, since WSA is determined through slow-wetting and shaking of the aggregates. Increases in the water-stable macro-aggregates were therefore related to increases in the mean weight diameter of aggregates subject to slow wetting and stirring after prewetting (wet mechanical cohesion), but not with those subject to fast wetting (slaking).

The comparison among the three parameters obtained in the Le Bissonnais method (MWD_{slow}, MWD_{fast}

Table 5. Micro-aggregate stability test: fragment distribution of sizes < 20 µm ($FSD_{microag < 20\ \mu m}$) and > 20 µm ($FSD_{microag > 20\ \mu m}$) and mean weight diameter ($MWD_{microag}$) values of the 20 studied soils. For each parameter, the soils are ranked from low to high values. Soils with «×» within the same column are not significantly different ($P > 0.05$)

Soil	$FSD_{microag < 20\ \mu m}$ (% in volume)	Homogen.* groups	Soil	$FSD_{microag < 20\ \mu m}$ (% in volume)	Homogen.* groups	Soil	$MWD_{microag}$ (µm)	Homogen. groups
Sariñena 4	45.0	×	Fraella 2	6.4	×	Fraella 2	9.1	×
SA 21/1	45.3	×	Tramaced 2	13.3	××	SA 20/5	12.5	×
SA 3/1	50.1	××	SA 20/5	17.2	××	Tramaced 2	13.5	×
Flumen	51.6	××	EC 2/E8	19.6	×××	EC 2/E8	16.3	××
SA 13/1	51.9	××	SA 16/1	24.3	×××	SA 16/1	16.7	××
SA 30/5	51.9	××	Callen 1	26.8	××××	SA 20/1	23.0	××
SA 27/2	56.0	××	Fraella 1	28.3	×××	Violada 10	25.8	××
SA 26/2	58.8	×××	Violada 10	29.9	××	Callen 1	26.8	××
SA 2/E7	59.4	×××	SA 20/1	30.4	××	SA 31/1	27.1	×××
SJF 8	64.0	×××	SA 31/1	31.5	×××	Fraella 1	30.4	×××
SA 31/1	68.5	×××	SJF 8	36.1	×××	SA 26/2	30.7	×××
SA 20/1	69.6	××	SA 2/E7	40.6	×××	SA 13/1	31.0	×××
Violada 10	70.2	××	SA 26/2	41.3	×××	SA 3/1	33.1	×××
Fraella 1	71.7	×××	SA 27/2	44.0	××	SJF 8	33.9	××××
Callen 1	73.3	××××	SA 30/5	48.1	××	SA 27/2	36.2	×××
SA 16/1	75.7	×××	SA 13/1	48.2	××	Flumen	41.8	×××
EC 2/E8	80.5	×××	Flumen	48.3	××	SA 2/E7	41.9	×××
SA 20/5	82.8	××	SA 3/1	50.0	××	SA 30/5	42.4	××
Tramaced 2	86.8	××	SA 21/1	54.7	×	SA 21/1	46.4	×
Fraella 2	93.7	×	Sariñena 4	55.1	×	Sariñena 4	47.1	×

* Homogen.: homogeneous groups.

and MWD_{stir}) indicates that MWD_{slow} and MWD_{stir} rank the soils in a similar order ($r_s = 0.52^{**}$), whereas MWD_{fast} is not correlated with the other two parameters (Table 6). The different ranking of the soils based on MWD_{fast} and MWD_{stir} indicates that they behaved differently to slaking and to the loss of mechanical cohesion when wet.

The micro-aggregate stability parameter $MWD_{microag}$ integrates the fragment size distribution of micro-aggregates measured in the Kemper and Rosenau method ($FSD_{microag}$), increasing with increases in the coarser fraction content ($FSD_{microag>20\mu m}$) and with decreases in the finer fraction content of soils ($FSD_{microag<20\mu m}$). The micro-aggregate stability parameters ($MWD_{microag}$, $FSD_{microag<20\mu m}$ and $FSD_{microag>20\mu m}$) ranked the soils in a different order than the macro-aggregate stability parameters (WSA, MWD_{slow}, MWD_{stir} and $SI_{stirring}$) (Table 6). Micro and macro-aggregates thus behave differently when subject to these destructive energies. Moreover, micro and macro-aggregates behaved differently against the same external stress or treatment (Kemper and Rosenau test). By contrast, $MWD_{microag}$ ranked the soils in a similar order than MWD_{fast} ($r_s = 0.58^{*}$) and $SI_{slaking}$ ($r_s = 0.56^{*}$). This result agrees with

Table 6. Spearman rank correlation coefficients among the stability parameters of 36 soils (35 soils for MWD_{fast} and $SI_{slaking}$ and 20 soils for $MWD_{microag}$, $FSD_{microag < 20\ \mu m}$ and $FSD_{microag > 20\ \mu m}$)

	MWD_{slow}	MWD_{fast}	MWD_{stir}	$SI_{slaking}$	$SI_{stirring}$	$MWD_{microag}$	$FSD_{microag < 20\ \mu m}$	$FSD_{microag > 20\ \mu m}$
WSA	0.72***	0.03^{NS}	0.65***	-0.11^{NS}	0.43**	0.12^{NS}	-0.15^{NS}	0.15^{NS}
MWD_{slow}		0.07^{NS}	0.52**	-0.13^{NS}	0.21^{NS}	-0.08^{NS}	-0.09^{NS}	0.10^{NS}
MWD_{fast}			0.24^{NS}	0.96***	0.31^{NS}	0.58*	–0.56*	0.56*
MWD_{stir}				0.11^{NS}	0.92***	0.40^{NS}	-0.36^{NS}	0.36^{NS}
$SI_{slaking}$					0.24^{NS}	0.56*	–0.50*	0.50*
$SI_{stirring}$						0.41^{NS}	-0.34^{NS}	0.33^{NS}
$MWD_{microag}$							–0.92***	0.91***

Levels of significance: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ^{NS} $P > 0.05$

the fact that MWD_{fast} and $SI_{slaking}$ ranked the soils in the same order ($P<0.05$) as the ranking based on the content of the coarser fragments ($FSD_{microag > 20\,\mu m}$), whereas the ranking was inverse ($P<0.05$) to that established by the content of finer fragments ($FSD_{microag < 20\,\mu m}$) measured in the Kemper and Rosenau method. The tolerance of soils to slaking thus increased with increases in the coarser fraction content and with decreases in the finer fraction content of soils measured in the Kemper and Rosenau method. These results indicate that slaking depends on micro-aggregate stability, and particularly the tolerance of soils to this process directly depends on the content of fragments greater than 20 µm.

Discussion

Laffan *et al.* (1996) set a threshold WSA value of 70% as indicative of soils resistant to macro-aggregate breakdown. Since only three soils (Fraella 2, Flumen and SA 31/1) had WSA values lower than 70% (Table 2), we determined that, according to the Kemper and Rosenau test, most of the studied soils were stable from the macro-aggregate point of view.

With respect to the breakdown of macro-aggregates in the standard test (Kemper and Rosenau, 1986), half of the soils had a high proportion ($FSD_{microag}$ around 80 ± 10%) of fragments < 20 µm (Table 5). These soils will be most susceptible to crusting according to Le Bissonnais *et al.* (1989), Chan and Mullins (1994), and Le Bissonnais (1996). These authors concluded that the development of crusts and seals were related to the FSD resulting from aggregate breakdown, so that the soils developing finer fragments were those more susceptible to crusting. Furthermore, Shainberg *et al.* (1997) and Farres (1987) indicated that the size of the detached and broken fragments determined the soil's rate of sealing, the physical properties of the seal (porosity and hydraulic conductivity) and the transportability of fragments (soil erosion).

Most of the 36 studied soils were homogeneous and quite stable at the macro-aggregate level as determined by the WSA (water stable aggregate) parameter (Table 2), but differed significantly among them and were quite unstable at the micro-aggregate level as determined by the $MWD_{microag}$ (mean weight diameter) parameter (Fig. 2 and Table 5). Macro- and micro-aggregate stability thus behaved differently so that both tests were needed for a comprehensive characterization of soils' structural stability.

According to the Le Bissonnais method, macro-aggregate stability of the studied soils decreased in the order slow wetting > stirring after prewetting > fast wetting, indicating that they were most susceptible to aggregate slaking (fast wetting). Amézketa *et al.* (1996) and Zhang and Horn (2001) found the same order of stability for 10 Californian and 9 China soils respectively, whereas Le Bissonnais and Arrouays (1997) found the order: stirring after prewetting > slow wetting > fast wetting, when using 3-5 mm-diameter aggregates of 12 soils.

The aggregate stability at a fast rate of wetting presented the highest coefficient of variation (CV of the mean MWD_{fast} = 35%, *versus* the CVs of 21% and 7% of the means MWD_{stir} and MWD_{low} respectively), reflecting the differential behaviour of these soils against fast wetting. Pierson and Mulla (1990) observed that the aggregate stability at a fast rate of wetting had a coefficient of variation (40%) that was nearly twice that for slow wetting.

Slaking induced by the fast wetting was the main destabilizing mechanism in these soils (32 out of the 36 soils had $SI_{slaking} < 0.5$; Table 4). Levy and Miller (1997) found that more than half of their studied soils had a stability ratio (ratio of the fast to slow structural indexes, equivalent to our $SI_{slaking}$ index) ≤ 0.5, suggesting a low level of aggregate stability. Paré *et al.* (1999) and Six *et al.* (2000) also found that soil disaggregation under conventional tillage and no-tillage was predominantly attributed to slaking forces, and Dinel *et al.* (1991) observed that slaking was again the dominating process involved in reducing aggregation in a group of marine clays.

On the other hand, most soils were quite tolerant to the mechanical shaking of aggregates (only 4 soils had $SI_{stirring} < 0.5$, indicating that they will be susceptible to the mechanical breakdown caused by the impact energy of water drops).

Based on these findings we concluded that irrigation management techniques should be devised on the basis of the most important limiting processes (slaking and crusting) for these soils. Thus, from an irrigation management point of view, the 32 soils susceptible to slaking of aggregates (those with $SI_{slaking} \leq 0.5$) should not be irrigated by such systems as furrow or flooding irrigation where the soils are rapidly wetted. In cases where furrow or flood irrigation systems are to be used, slaking could be prevented or minimized by forming raise-beds (Chan and Mullins, 1994), and/or adding organic matter or hydrophobic polymers such as polyacrylamides (Ferruzzi *et al*., 2000). On the other hand, the 4 soils susceptible to the loss of wet mechanical cohesion of aggregates (SA 92/1, Fraella 2, Flumen, and Callen 1) should not be irrigated by such systems as sprinkler irrigation and/or should be mulched by cover crops or crop residues to prevent the impact energy of the water drops.

The similar ranking of soil stability based on the parameters WSA (Kemper and Rosenau method) and MWD_{slow} and MWD_{stir} (Le Bissonnais method) contrast with the results of Amézketa *et al*. (1996) for 10 Californian soils, where WSA and the three MWD parameters were not correlated.

Contrasting results were also obtained when comparing the ranking of the soils on the basis of the 3 MWD parameters. In our study, MWD_{slow} and MWD_{stir} rank the soils in a similar order ($r_s = 0.52^{**}$), whereas MWD_{fast} does not rank the soils in the same order. Le Bissonnais and Arrouays (1997) found that the ranking of the soils on the basis of the 3 MWD parameters was different, whereas Amézketa *et al*. (1996) found that these parameters ranked the soils in the same order of aggregate stability. These contrasting results suggest that the breakdown processes of the macro-aggregates subject to the slow, fast, and stirring treatments were affected by different physical and/or chemical soil properties.

Finally, since the aggregate-stability processes are soil-dependent and cannot be generalized, an emphasis should be made at developing and validating simple and reproducible laboratory tests aimed at establishing concurrently the macro- and micro-aggregate stability of soils.

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