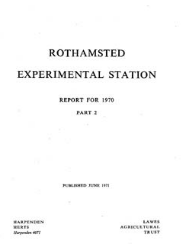
ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1970 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1970

PART 2

Full Table of Content

Relationships Between the Composition of Soils and Physical Measurements Made on Them

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Relationships Between the Composition of Soils and Physical Measurements made on them

R. J. B. WILLIAMS

The good drainage and aeration of soils that is essential for roots to grow satisfactorily can be ensured only by enough pores of the right sizes together with cracks and fissures leading through the soil and subsoil. Pore space is lost when aggregates are 'slaked', either by water or mechanically when soil is compressed or deformed. In the work described in this paper the stability and strength of the aggregates in 189 soils were measured, and measurements related to each other and to the compositions of the soils. The laboratory tests simulated some of the conditions in field soils, created either by weather or cultivations. They involved two physical processes, disintegration (slaking) and cohesion. Slaking can be caused by the capillary action of water, or by mechanical pressure on dry soil, or by both. Cohesion expresses the resistance of aggregates to mechanical forces that might break them—important in assessing the effects of implements intended to make soil finer.

The soils were mainly from arable land in Great Britain, wherever possible from sites of field experiments about which there was already some other information. Thirty-seven soils were from Woburn and 27 from Rothamsted; the other British soils came from the following counties: Bedford, Buckingham, Cambridge, Cardigan, Cheshire, Cornwall, Derby, Dorset, Essex, Gloucestershire, Hampshire, Hereford, Hertford, Huntingdon, Kent, Lancashire, Leicester, Lincoln, Norfolk, Northampton, Nottingham, Shropshire, and Suffolk. There were also 13 soils from Ireland.

The soils were prepared (as air-dry aggregates) in a standard way to obtain comparable results; the tests were made with simple and easily constructed apparatus. Table 1 shows groupings of soils. More than half were arable topsoils. A sixth were rich in organic matter because of organic manuring; a sixth were grassland soils and a few were from woodland and subsoils. Nearly three-quarters of the soils had less than 2% organic carbon—representative of much arable land in England.

TABLE 1

Description of soil used

History	Number of soils	Major groups	Percentage
Fallows	9		
Subsoils	10	118	62
Arable topsoils	99		
Arable (sewage sludge or compost treated)	17		
Arable (receiving farmyard manure)	14	34	18
Woodland	3		
Grassland (ploughed)	17		
Grassland (under ley)	5	37	20
Grassland (permanent pasture)	15		
Soils $>2\cdot00\%$ organic carbon	49	—	—
Soils $<2\cdot00\%$ organic carbon	140	—	—

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Methods

The physical methods used were described by Williams and Cooke (1961). A portion of each soil was air-dried and a fraction passing a 2 mm sieve was used to measure bulk density, water-holding capacity and mechanical composition, and for chemical analyses. The remainder was used to prepare aggregates for the tests by freezing, thawing and air-drying. It was wetted until moist, but not sticky, packed into polythene tubing and maintained at −15°C for three days. The sample was removed from the tube, allowed to thaw, dry and disintegrate; drying at room temperature was assisted by a fan. Aggregates with diameters in the range 4–6 mm were separated by round-holed sieves, using no force, and were stored so that they could not be mechanically damaged.

Bulk density (BD). British Standards Institution (1948) method.

Water-holding capacity (WHC). 20 g soil (<2 mm) were saturated with water for several hours; the water remaining after draining overnight was measured.

pH. pH was measured in a 1 : 2·5 suspension by glass electrode.

Water-slaking (I/WS). The percentage change in volume of a column of 30 g of 4–6 mm aggregates when wetted from below was measured (Williams & Cooke, 1961). Changes in the soils during slaking were observed with a hand lens.

Dry (mechanical) slaking (I/DS). 100 g of 4–6 mm aggregates in a column were compressed at 7·03 kg/cm^2 for 1 minute; percentage loss in volume was measured.

Total mechanical slaking (I/MS). The two tests were combined by compressing soil already slaked by water. (The pressure used, 7 kg/cm^2, caused about half as much compaction as pressure six times as large.)

Breaking strength (BS). The load needed to split a section (25 mm long and 25 mm diameter) of the compressed and air-dried cylinder produced by the previous mechanical slakings was measured. A polished steel penetrometer, 12·5 mm diameter with a hemispherical tip, was used and the section from the soil cylinder that was closest to the plunger when it was formed by mechanical slaking was chosen.

Mechanical composition. The gravel and coarse organic debris in the soil used for the water-slaking test were separated by elutriation and sieving. Coarse sand (2·0–0·2 mm) and fine sand (0·20–0·02 mm) were separated by decanting and sieving after destroying organic matter by hydrogen peroxide.

A separate portion of the original sample was used to measure % silt (0·02–0·002 mm) and % clay (<0·002 mm).

Loss on ignition. Percentage loss on ignition of <2 mm soil heated at 800°C in a muffle furnace for 2 hours was measured.

Chemical measurements. Williams' (1948) manometric method was used to measure %$CaCO_3$. %N was referred to <2 mm soil dried at 105°C, by a Kjeldahl method (Bremner, 1960) using Cu and Se as catalysts. Walkley and Black's method (Walkley,

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1935) was used on <0·5 mm soil to measure % organic carbon; the results given here are as determined.

Table 2 gives correlation coefficients between the physical and chemical measurements on the soils.

TABLE 2

Correlation coefficients between soil composition variates

	Coarse particles 6–0·02 mm	Coarse particles 6–0·2 mm	OC %	N %	COM %	Silt %	Clay %
			Arable soils (DF 145)				
% Coarse particles (CP) (6–0·02 mm)	1·00	—	—	—	—	—	—
% Coarse particles (6–0·2 mm)	0·85	1·00	—	—	—	—	—
% Organic carbon (OC)	−0·51	−0·35	1·00	—	—	—	—
% Total nitrogen (N)	−0·60	−0·43	0·92	1·00	—	—	—
% Coarse organic matter (COM) (2–6 mm)	−0·22	−0·17	0·41	0·39	1·00	—	—
% Silt (0·02–0·002 mm)	−0·73	−0·69	0·30	0·35	0·14	1·00	—
% Clay (< 0·002 mm)	−0·78	−0·62	0·35	0·42	0·13	0·17	1·00
			Grassland soils (DF 35)				
% Coarse particles (6–0·02 mm)	1·00	—	—	—	—	—	—
% Coarse particle (6–0·2 mm)	0·85	1·00	—	—	—	—	—
% Organic carbon	−0·58	−0·39	1·00	—	—	—	—
% Total nitrogen	−0·70	−0·42	0·92	1·00	—	—	—
% Coarse organic matter (2–6 mm)	−0·24	−0·21	0·40	0·37	1·00	—	—
% Silt (0·02–0·002 mm)	−0·84	−0·71	0·39	0·51	0·27	1·00	—
% Clay (< 0·002 mm)	−0·72	−0·69	0·05	0·24	−0·08	0·40	1·00

Results

Table 3 gives average values for each of the properties measured. Grassland soils slaked much less readily than arable soils in water but the two differed less in the dry slaking test. Test cylinders formed by compacting arable soils were much stronger than those from grassland. Arable soils had larger bulk densities, but held less water and contained less N and C than grassland soils. Differences of these kinds were expected.

The reproducibility of the tests employed was examined by making ten replicate measurements on seven soils chosen for widely different mechanical compositions and organic carbon contents. Table 4 gives average values and standard deviations. When soils were very stable to water (i.e. per cent loss in pore space on wetting was small), the value was not accurately determined. With values smaller than 5%, standard deviations tended to be of the same size. This was because stable soils were usually rich in organic carbon and clay, which made them swell without slaking and stick to the tube used in the test, obscuring movement of the column of soil. Larger instabilities were measured more accurately. The other properties were also measured quite accurately. Measuring the very small loss in pore space accurately for groups of very stable soils is not important, except when comparing the effects of experimental treatments that may alter physical properties. Where accurate measures are needed on stable soils an alternative, more sensitive, procedure described by Williams (1963) can be used.

Comparisons of individual soil properties

The soil properties considered most likely to alter the physical attributes measured were organic matter content and mechanical composition (especially the proportions of

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TABLE 3

Summary of results of physical tests and chemical analyses on 189 soils

Soil test or analysis	All soils (189)			Arable soils (147)			Grassland soils (37)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
% Water slaking instability (I/WS)	−3·4	20·2	60·1	−3·4	22·4	60·1	−2·1	7·7	42·0
% Dry slaking instability (I/DS)	8·6	21·6	48·5	8·6	21·6	44·9	10·9	19·8	37·3
% Total mechanical slaking (I/MS)	27·4	59·0	79·2	44·9	60·1	79·2	27·4	54·2	65·3
Breaking strength (kg) (BS)	0·12	5·99	17·00	0·12	6·10	17·00	1·05	4·49	14·75
Bulk density (< 2 mm soil g/ml) (BD)	0·76	1·26	1·63	0·76	1·28	1·63	0·85	1·17	1·39
% Water holding capacity (< 2 mm soil) (WHC)	12·8	49·4	99·3	12·8	47·1	85·4	29·4	60·0	99·3
Absolute density (g/ml)	2·17	2·51	2·75	2·25	2·53	2·75	2·17	2·46	2·63
pH in water	3·8	7·0	8·8	3·8	7·1	8·3	5·2	6·6	7·9
% Free calcium carbonate	0·0	3·9	82·8	0·0	3·7	82·8	0·0	2·2	61·6
% Organic carbon (Walkley & Black)	0·21	1·72	7·05	0·21	1·54	4·06	1·02	2·52	7·05
% Total nitrogen	0·04	0·20	0·68	0·04	0·18	0·42	0·11	0·27	0·68
% Coarse organic matter (2–6 mm) (COM)	0·0	0·11	1·01	0·00	0·08	0·69	0·01	0·21	1·01
% Coarse particles (6–0·02 mm) (CP)	11·9	59·8	91·8	11·9	61·4	91·8	22·5	54·1	84·9
% Coarse particles (6–0·2 mm)	0·1	31·2	84·1	0·1	33·2	84·1	4·3	25·5	72·1
% Silt (0·02–0·002 mm)	0·5	17·3	64·7	2·8	16·5	64·7	4·4	19·9	56·7
% Clay (< 0·002 mm)	0·4	16·2	57·6	0·4	15·8	57·6	6·0	18·0	35·8

TABLE 4

Reproducibility of soil physical test on different soils

		A	B	C	D	E	F	G
Soil composition	% Organic carbon	0·50	0·64	1·11	2·21	2·63	0·67	2·34
	% Coarse particles	48·0	79·0	81·8	56·0	39·8	82·0	54·6
	% Clay	29·3	10·3	8·0	22·3	23·7	9·7	22·5
Physical test								
% Water slaking instability		10·01 ±2·72	—	4·12 ±3·02	—	−1·74 ±1·23	36·50 ±2·34	—
% Dry slaking instability		6·71 ±0·66	15·50 ±1·19	17·36 ±0·79	7·86 ±0·44	—	—	—
% Total mechanical slaking		55·72 ±1·44	64·8 ±1·48	51·4 ±1·35	59·47 ±2·25	—	—	—
Breaking strength (kg)		9·97 ±0·72	5·28 ±0·66	1·45 ±0·19	8·07 ±1·53	—	—	—
Bulk density (< 2 mm soil) (g/ml)		1·274 ±0·008	1·454 ±0·014	—	—	—	—	—
% Water holding capacity (< 2 mm soil)		—	—	49·47 ±1·55	—	—	—	53·57 ±1·70

coarse particles of sand and gravel). These are examined in Tables 5 (gravel + coarse sand), 6 (gravel + coarse sand + fine sand) and 7 (organic carbon), where the soils are divided into groups of equal numbers (to provide comparable results) with increasing % organic C, or increasing % coarse particles. Correlation coefficients between each soil physical test and each soil property measured were calculated (Table 8), also linear regression coefficients (Table 9). In the following sections the effects of soil properties on each of the measurements made are discussed, individually from Tables 3, 5, 6, 7, 8 and 9 and from Figs. 1–5, which plot some detailed comparisons for bulk densities, the instability tests, and soil cylinder strengths.

Correlations between the results of the six tests on the soils are shown in Table 10 for arable and grassland soils separately. Instability to water was well correlated with instability to mechanical pressure by arable but not by grassland soils; as might be expected, there was some correlation between total instability to water and pressure combined, and to both water slaking and dry slaking tested separately. Breaking strength of cylinders was correlated with instability both in water and on dry slaking for arable soils, but only with dry slaking for grassland soils. Bulk density was correlated with amount of water slaking of arable soils and with wet slaking, total slaking, and breaking strengths of cylinders for grassland soils. Water-holding capacity (WHC) was well correlated with bulk density in grassland, but less closely in arable soils; WHC was correlated with results of all slaking tests on arable soils but was not closely related to dry mechanical slaking of grassland soils.

Bulk density (BD). The relationship between apparent density and absolute density shows total pore space in soils. Arable soils as a whole were more dense, and the range of values was greater, than grassland soils. Soils with more coarse particles tended to be more dense than finer textured soils (Fig. 1a) and relationships were clearer when the 'coarse' fraction included fine sand. The densities of groups of soils with more than 2% organic carbon differed considerably from those with less than 2% (Fig. 1b). The effects of organic carbon content were clear and consistent (Table 7, Fig. 1c and d), with bulk

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TABLE 5

Effects of increasing amounts of coarse mineral particles (6–0·2 mm) on soil properties

Range of particles 6–0·2 mm %	Number of soils	Particles 6–0·2 mm Mean %	Bulk density g/ml (< 2 mm soil)	Instability I/WS %	Instability I/DS %	Instability I/MS %	Breaking strength kg	Organic carbon %	Total nitrogen %	Absolute density g/ml
All soils										
0·1– 5·9	21	2·9	1·23	19·4	19·0	54·6	9·64	1·98	0·20	2·49
6·0–10·1	21	8·6	1·22	8·6	16·0	56·1	8·84	1·91	0·22	2·46
10·3–14·7	21	12·6	1·17	4·3	16·3	51·7	6·68	2·40	0·27	2·45
15·0–22·5	21	18·2	1·23	9·6	14·9	57·5	8·96	1·95	0·22	2·47
22·7–30·0	21	25·9	1·21	11·8	18·2	58·4	5·96	2·09	0·24	2·48
30·6–40·0	21	35·4	1·26	20·0	20·6	61·6	5·58	1·35	0·16	2·55
40·9–55·6	21	47·3	1·32	30·4	27·5	63·6	4·88	1·08	0·13	2·56
55·9–65·2	21	60·4	1·35	37·3	31·4	62·6	2·13	1·07	0·12	2·57
66·5–84·1	21	69·4	1·33	38·5	30·9	62·8	2·13	0·96	0·11	2·57
0·1–84·1	189	31·2	1·26	20·0	21·5	58·8	6·04	1·60	0·19	2·51
140 soils with < 2·00% organic carbon										
0·1– 8·5	20	3·4	1·24	22·0	19·6	56·6	9·90	1·28	0·16	2·52
8·7–14·7	20	10·9	1·30	10·9	15·9	57·1	9·37	1·35	0·17	2·51
15·2–27·0	20	20·6	1·24	11·5	15·7	59·1	8·11	1·38	0·17	2·52
28·0–38·8	20	33·6	1·31	23·8	20·3	62·7	6·32	1·19	0·14	2·55
39·3–55·6	20	47·4	1·33	34·2	28·8	64·3	4·97	0·93	0·11	2·57
55·9–65·5	20	60·5	1·35	37·2	30·6	63·2	2·29	0·91	0·11	2·58
66·0–84·1	20	69·6	1·33	38·5	30·7	62·6	2·17	0·99	0·11	2·57
0·1–84·1	140	35·1	1·30	25·4	23·1	60·8	6·16	1·14	0·14	2·54
49 soils with > 2·00% organic carbon										
2·1–12·4	16	7·8	1·11	0·7	17·6	49·3	6·94	3·22	0·35	2·37
12·7–23·3	16	16·7	1·14	2·6	15·1	52·4	6·16	3·04	0·33	2·41
23·6–63·8	17	34·4	1·18	9·4	21·3	56·8	4·29	2·50	0·27	2·46
2·1–63·8	49	19·9	1·14	4·3	18·1	52·9	5·76	2·91	0·31	2·41

TABLE 6

Effects of increasing proportions of gravel, coarse and fine sand (6–0·02 mm) on soil properties

Range of particles 6–0·02 mm %	Number of soils	Particles 6–0·02 mm Mean %	Bulk density g/ml (< 2 mm soil)	Instability I/WS %	Instability I/DS %	Instability I/MS %	Breaking strength kg	Organic carbon %	Total nitrogen %	Absolute density g/ml
All soils										
11·9–35·2	21	26·0	1·20	5·8	13·1	50·5	11·36	2·39	0·288	2·41
35·6–44·6	21	40·2	1·20	11·4	16·8	54·4	8·16	2·18	0·251	2·41
45·4–50·5	21	48·5	1·22	11·4	16·5	57·1	7·84	1·99	0·226	2·48
50·7–54·6	21	52·3	1·21	8·6	17·0	52·5	6·43	1·94	0·229	2·48
54·7–61·0	21	57·7	1·24	10·7	18·0	57·9	6·24	1·63	0·179	2·52
62·3–71·2	21	66·2	1·25	21·4	21·4	62·0	6·37	1·32	0·161	2·53
71·6–71·5	21	77·5	1·29	33·6	27·5	63·3	3·45	1·25	0·144	2·55
81·6–84·5	21	82·6	1·32	36·4	31·0	63·5	2·20	1·14	0·128	2·61
84·6–91·8	21	87·3	1·40	40·8	33·7	62·5	2·36	0·61	0·066	2·61
11·9–91·8	189	59·8	1·26	20·0	21·7	58·2	6·04	1·60	0·186	2·51
Soils with < 2·00% organic carbon										
22·3–44·6	20	35·1	1·28	16·1	16·6	55·6	11·29	1·32	0·170	2·50
47·4–51·8	20	49·8	1·28	14·3	15·2	59·2	9·33	1·40	0·176	2·52
52·2–60·9	20	56·9	1·27	13·1	17·2	59·3	6·99	1·27	0·149	2·54
62·3–71·2	20	66·3	1·27	22·0	21·4	62·0	6·47	1·26	0·158	2·53
71·6–81·5	20	77·8	1·29	34·6	27·4	64·0	3·55	1·15	0·147	2·55
81·6–84·6	20	82·8	1·32	36·7	30·2	63·5	2·46	1·04	0·121	2·57
84·7–91·8	20	87·5	1·40	40·8	33·6	62·5	2·40	0·58	0·064	2·61
22·3–91·8	140	65·2	1·30	25·4	23·1	60·9	6·07	1·14	0·141	2·54
Soils with > 2·00% organic carbon										
11·9–39·7	16	27·1	1·14	1·1	12·0	48·3	8·82	3·26	0·369	2·37
40·3–51·0	16	46·1	1·12	2·2	17·9	53·1	5·17	2·83	0·310	2·43
51·2–81·9	17	59·3	1·17	10·1	22·2	56·0	3·45	2·64	0·267	2·45
11·9–81·9	49	44·5	1·14	4·6	17·5	52·5	5·76	2·90	0·314	2·42

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TABLE 7

Effects of percentage of organic matter on soil properties

Range organic carbon %	Number of soils	Organic carbon Mean %	Bulk density g/ml (< 2 mm soil)	Instability I/WS %	Instability I/DS %	Instability I/MS %	Breaking strength kg	Particles 6–0·02 mm %	Total nitrogen %	Absolute density g/ml
All soils										
0·18–0·58	21	0·42	1·41	35·9	29·4	60·4	5·83	76·0	0·056	2·60
0·58–0·96	21	0·72	1·36	35·7	25·1	63·4	5·61	73·6	0·093	2·59
0·97–1·10	21	1·03	1·31	25·8	21·5	61·7	6·56	65·6	0·135	2·55
1·13–1·29	21	1·22	1·25	27·5	23·4	61·8	7·77	62·1	0·147	2·53
1·31–1·50	21	1·40	1·26	25·6	21·0	61·7	5·03	64·7	0·174	2·53
1·50–1·72	21	1·62	1·25	15·1	21·7	59·4	5·60	58·7	0·192	2·50
1·75–2·10	21	1·92	1·22	5·0	16·5	56·2	6·90	49·9	0·224	2·48
2·11–2·65	21	2·44	1·16	8·7	19·1	55·9	5·19	47·9	0·260	2·46
2·66–6·90	21	3·68	1·11	0·6	16·2	48·6	5·70	39·4	0·391	2·35
0·18–6·90	189	1·60	1·26	20·0	21·5	58·8	6·02	59·8	0·186	2·51
Arable soils including fallows and subsoils										
0·18–0·59	24	0·44	1·40	36·8	29·6	60·9	5·52	77·1	0·059	2·60
0·59–1·00	24	0·81	1·34	32·6	22·9	62·1	6·29	70·3	0·106	2·58
1·01–1·41	24	1·21	1·26	25·4	19·2	61·0	8·37	57·1	0·153	2·52
1·42–2·02	24	1·68	1·23	10·6	17·4	57·6	7·61	48·2	0·198	2·50
2·10–3·54	22	2·66	1·19	6·5	17·6	55·0	6·68	44·9	0·287	2·43
0·18–3·54	118	1·34	1·28	22·6	21·4	59·3	6·90	59·9	0·158	2·53
FYM, compost, and sewage sludge treated soils										
0·85–1·31	11	1·17	1·30	35·0	28·1	65·4	3·98	77·2	0·141	2·55
1·34–1·65	11	1·48	1·27	31·8	25·8	63·0	3·97	72·6	0·181	2·52
1·67–3·85	12	2·44	1·19	7·7	19·1	56·5	5·87	49·8	0·281	2·45
0·85–3·85	34	1·72	1·25	24·3	24·2	61·4	4·64	66·0	0·203	2·50
Grassland soils (permanent grass, leys, soils ploughed out of grass)										
1·02–1·50	12	1·20	1·29	19·7	23·8	61·1	4·83	65·4	0·148	2·56
1·68–2·25	12	1·91	1·20	2·7	17·9	56·1	5·11	55·8	0·221	2·49
2·30–6·90	13	3·82	1·04	1·2	17·9	46·0	4·12	41·9	0·391	2·35
1·02–6·90	37	2·35	1·17	7·7	19·8	54·2	4·67	54·0	0·257	2·46

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TABLE 8

Coefficients of correlations between physical tests on soils and their mechanical and chemical properties

	Coarse particles		Fine particles		Organic matter		
	6–0·02 mm %	6–0·2 mm %	silt %	clay %	C %	N %	coarse (2–6 mm) %
Bulk density (BD)							
Arable	0·42	0·41	−0·38	−0·17	−0·59	−0·62	−0·34
Grass	0·42	0·35	−0·27	0·04	−0·84	−0·76	−0·61
All	0·44	0·40	−0·36	−0·16	−0·70	−0·70	−0·49
Water holding capacity (WHC)							
Arable	−0·63	−0·53	0·36	0·52	0·65	0·66	0·37
Grass	−0·57	−0·39	0·34	0·17	0·86	0·90	0·40
All	−0·61	−0·48	0·33	0·46	0·74	0·76	0·44
Water slaking instability (I/WS)							
Arable	0·80	0·73	−0·56	−0·62	−0·64	−0·68	−0·28
Grass	0·50	0·54	−0·35	−0·31	−0·50	−0·55	−0·43
All	0·72	0·63	−0·48	−0·55	−0·63	−0·68	−0·37
Dry slaking instability (I/DS)							
Arable	0·83	0·79	−0·64	−0·63	−0·35	−0·46	−0·16
Grass	0·81	0·69	−0·68	−0·74	−0·30	−0·47	0·03
All	0·78	0·69	−0·59	−0·61	−0·36	−0·48	−0·13
Total mechanical slaking (I/MS)							
Arable	0·57	0·52	−0·35	−0·48	−0·44	−0·44	−0·11
Grass	0·61	0·39	−0·49	−0·14	−0·80	−0·86	−0·29
All	0·58	0·49	−0·38	−0·40	−0·62	−0·63	−0·26
Breaking strength (BS)							
Arable	−0·73	−0·63	0·47	0·69	0·05	0·15	−0·01
Grass	−0·36	−0·42	−0·35	0·61	−0·34	−0·27	−0·23
All	−0·61	−0·57	0·40	0·62	−0·12	−0·03	−0·11

density decreasing as carbon increased. By contrast, clay and silt contents had little effect on bulk density (Table 8). Silt usually behaved in much the same way as clay, though most relationships were less closely correlated than for clay. (The silt content rarely had independent effects on the results of the stability tests and it is not discussed in detail.) 'Coarse' organic matter (2–6 mm) rarely had large and significant effects on the properties measured and does not merit detailed discussion.

Water-holding capacity (WHC). The simple laboratory measurement of water-holding capacity at low tension was made on <2 mm soil; the values obtained always much exceed field capacity but they are quite reproducible. WHC diminished with increasing proportions of fine particles and increased linearly with increasing organic carbon contents—both for arable and grassland soils. The slaking in water of small aggregates affects the amount of water retained by the sample because it modifies interparticle voids and the tension between the soil particles. The soils were wetted long enough for the organic matter to become saturated.

The percentages of coarse particles (6–0·02 mm) were more closely correlated with WHC ($r = -0{\cdot}61$) than were the percentages CP (6 mm–0·2 mm) excluding fine sand ($r = -0{\cdot}48$). The negative correlation of coarse particles with WHC was much less

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TABLE 9

Coefficients of linear regression of physical and chemical properties on results of physical tests

	% Coarse particles (6–0·02 mm)				% Clay (< 0·002 mm)			
	b	SE	t	% Associated variance	b	SE	t	% Associated variance
Water slaking instability								
All	0·63	±0·045	14·04	51·1	−0·86	±0·096	8·98	29·8
Arable	0·65	±0·41	16·03	63·7	−0·88	±0·092	9·55	38·2
Grass	0·41	±0·119	3·43	23·0	−0·57	±0·293	1·93	7·1
Dry mechanical slaking								
All	0·34	±0·019	17·38	61·5	−0·47	±0·044	10·55	37·0
Arable	0·34	±0·019	18·22	69·4	−0·45	±0·045	9·86	39·7
Grass	0·37	±0·044	8·28	65·2	−0·75	±0·115	6·54	53·7
Total mechanical slaking								
All	0·22	±0·022	9·69	33·1	−0·27	±0·045	5·92	15·3
Arable	0·18	±0·021	8·40	32·3	−0·26	±0·039	6·66	22·9
Grass	0·35	±0·075	4·62	36·1	−0·18	±0·213	0·85	−0·8
Breaking strength								
All	−1·36	±0·128	10·67	37·5	2·47	±0·227	10·91	38·6
Arable	−1·57	±0·122	12·85	52·9	2·60	±0·224	11·63	47·9
Grass	−0·71	±0·305	2·31	10·8	2·65	±0·583	4·55	35·4
Bulk density								
All	0·28	±0·042	6·73	19·0	−0·19	±0·083	2·28	2·2
Arable	0·24	±0·043	5·54	16·9	−0·17	±0·082	2·07	2·2
Grass	0·35	±0·128	2·75	15·4	0·08	±0·317	0·24	−2·7
Water holding capacity								
All	−0·52	±0·049	10·48	36·6	0·71	±0·099	7·17	21·1
Arable	−0·46	±0·048	9·75	39·2	0·67	±0·091	7·39	26·9
Grass	−0·67	±0·165	4·09	30·4	0·45	±0·440	1·02	0·1

	% Organic carbon				% Total nitrogen			
Water slaking instability								
All	−10·35	±0·923	11·21	39·9	−110·10	±8·63	12·75	46·2
Arable	−12·77	±1·25	10·19	41·3	−121·79	±11·01	11·06	45·4
Grass	−4·55	±1·30	3·41	22·9	−54·95	±14·03	3·92	28·5
Dry mechanical slaking								
All	−2·85	±0·545	5·22	12·3	−37·91	±5·06	7·49	22·7
Arable	−3·50	±0·769	4·55	11·9	−42·01	±6·63	6·34	21·1
Grass	−1·50	±0·80	1·80	6·6	−26·11	±8·26	3·16	20·0
Total mechanical slaking								
All	−4·35	±0·397	10·96	38·8	−43·29	±3·91	11·06	39·2
Arable	−3·36	±0·565	5·94	19·0	−30·45	±5·16	5·90	18·8
Grass	−5·01	±0·623	8·03	63·8	−59·80	±6·00	9·96	73·2
Breaking strength								
All	−5·18	±2·98	1·74	1·1	−12·15	±29·73	0·41	−0·4
Arable	2·52	±4·32	0·58	−0·4	73·70	±38·94	1·89	1·7
Grass	−7·24	±3·37	2·15	9·1	−64·07	±38·60	1·66	4·6
Bulk density								
All	−8·46	±0·621	13·53	49·2	−82·40	±6·19	13·31	48·4
Arable	−8·25	±0·934	8·83	34·5	−78·40	±8·30	9·44	37·6
Grass	−7·66	±0·849	9·02	69·1	−77·70	±11·27	6·89	56·4
Water holding capacity								
All	11·76	±0·770	15·27	55·2	119·42	±7·34	16·27	58·4
Arable	11·65	±1·14	10·24	41·6	108·84	±10·16	10·71	43·8
Grass	11·19	±1·10	10·16	73·9	129·78	±10·87	11·93	79·7

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TABLE 10

Correlation coefficients between results of physical tests on arable and grassland soils

	Slaking tests: Water (I/WS)	Slaking tests: Dry (I/DS)	Slaking tests: Total (wet + pressure) (I/MS)	Breaking strength of soil cylinders (BS)	Bulk density (BD)	Water-holding capacity (WHC)
			Arable soils (145)			
I/WS	1·00	—	—	—	—	—
I/DS	0·71	1·00	—	—	—	—
I/MS	0·59	0·52	1·00	—	—	—
BS	−0·49	−0·67	−0·29	1·00	—	—
BD	0·53	0·30	0·28	−0·02	1·00	—
WHC	−0·71	−0·56	−0·46	0·34	−0·55	1·00
			Grassland soils (45)			
I/WS	1·00	—	—	—	—	—
I/DS	0·38	1·00	—	—	—	—
I/MS	0·51	0·44	1·00	—	—	—
BS	0·10	−0·54	0·28	1·00	—	—
BD	0·59	0·14	0·69	0·42	1·00	—
WHC	−0·63	−0·28	−0·79	−0·42	−0·81	1·00

than the positive correlations with % organic carbon ($r = 0{\cdot}74$) or with % total nitrogen ($r = 0{\cdot}76$). As with bulk density, water-holding capacity was little influenced by differences in the form of organic matter caused by manuring or by a history including grassland.

Slaking by water (I/WS). This, the most important of the measurements made, shows whether soil aggregates are stable when wetted, and lose only trivial amounts of pore space, or whether they slake to release individual particles, become compact and lose much pore space. Most soils with much coarse material (>0·02 mm) slake nearly completely; residual pore space, on which aeration and drainage depend, is then determined by relative proportions of coarse and fine materials and by the irregularities in packing. When the fine particles are completely released and are enough to fill the pores between gravel, coarse and fine sand, slaking can be disastrous because, with pores completely occupied by solids, no space is left for air and water. This can happen with sandy clay soils, in which sand is enough to separate the clay and prevent it acting as a cement to give stable aggregates, and clay and silt are enough to fill the spaces between the sand particles. The upper limit of loss in pore space in the water slaking test is about 70%. This was empirically measured on ranges of sand particles artificially aggregated by a strong sucrose solution and then tested in the water instability apparatus of Williams and Cooke (1961); the aggregates were, of course, completely unstable when wetted. The one-third of pore space remaining varies slightly with shape of particles and their packing characteristics, and whether they can move and resort. Particles helped to move by mechanical agitation, or by moving water, can pack more closely.

In Table 11 the soils are grouped by the loss in pore space on water slaking. The soils become more unstable as percentages of gravel + coarse sand + fine sand (6–0·02 mm) increase and as silt + clay diminishes. The most stable soils tend to contain most organic carbon (nearly three times as much as the very unstable soils). Soils that lost no more than one-tenth of their pore space when wetted contained, on average, 1·5% organic carbon.

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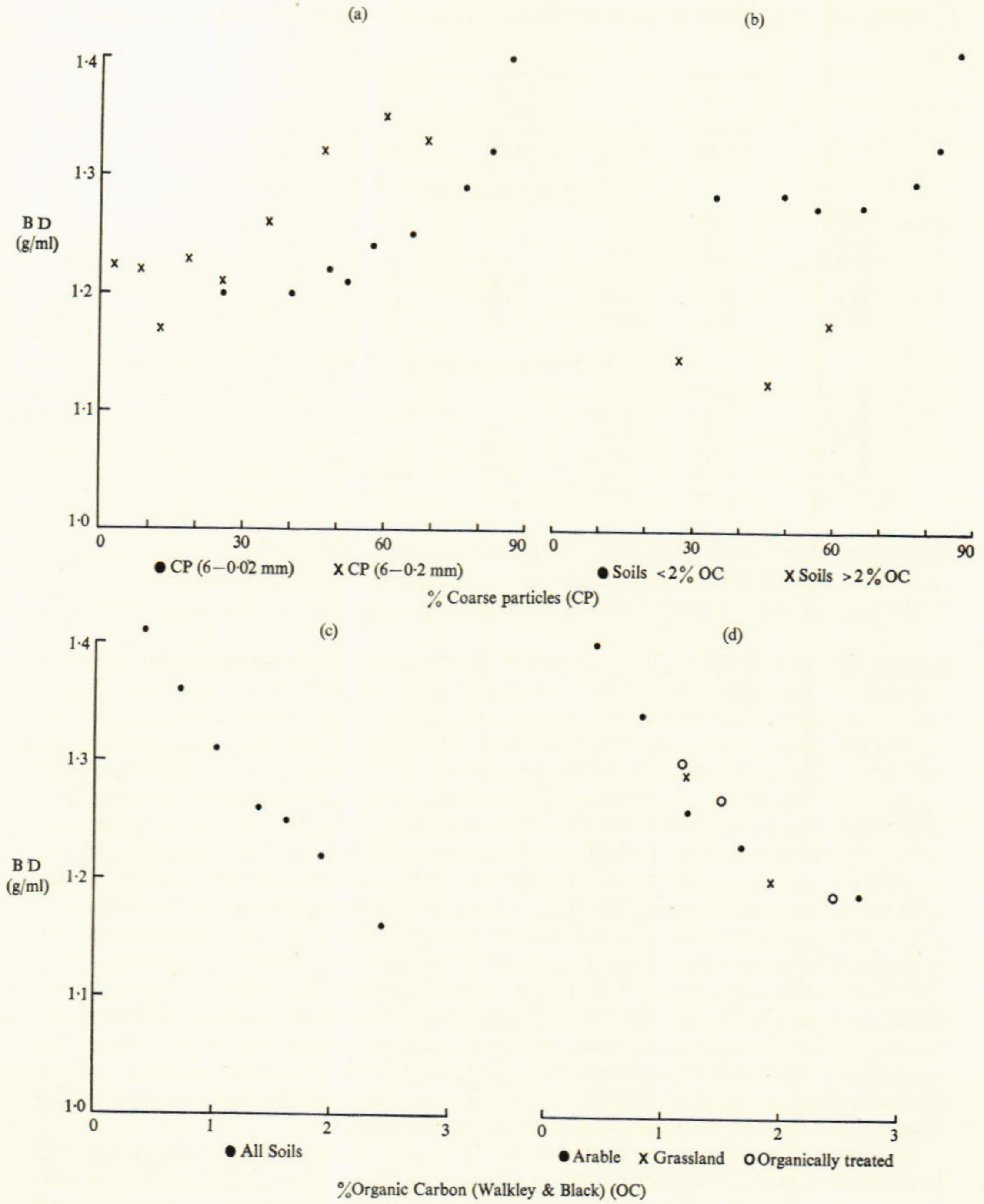

Fig. 1. The effect of soil composition upon the bulk density of <2 mm soil.

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TABLE 11

Groups of soils arranged by their instability in water, and average mechanical compositions of the groups

Number of soils	Water slaking instability % loss in pore space	Mechanical composition: Coarse particles (6–0·02 mm)	Silt (0·02–0·002 mm)	Clay (< 0·002 mm)	Organic carbon %
55	(−2 to +5)	44·0	21·7	21·2	2·57
26	(+5 to +15)	51·6	20·3	18·2	1·55
33	(+15 to +25)	51·9	21·6	17·9	1·44
44	(+25 to +40)	75·6	9·9	9·2	1·02
30	(+40 to +70)	77·7	8·5	8·4	0·93

The two constituents that had most effect on slaking are easily determined. Gravel and sand fractions (6–0·02 mm), when large, dominate physical properties and their amounts should always be measured in work on physical properties. The simple 'Walkley and Black' method for organic carbon measures the readily oxidisable organic matter in soils (Bremner & Jenkinson, 1960) which is most likely to stabilise aggregates. An example of the greater value of this measure than of total carbon was shown by one soil in this series that contained 0·5% C by the Walkley and Black method, the water slaking instability was 15% (which is large for a clay loam). Combustion analysis showed that it contained 3% total carbon; clearly most was in very resistant forms having little influence on soil stability.

As was expected, grassland soils were, on average, much more stable than arable soils and the range of instabilities measured was smaller (Table 3). Grassland soils with more than 1·5% C were almost completely stable; groups of arable soils with as much organic carbon were unstable and there was little differences between the arable soils whether or not they had received organic manures (Fig. 2c).

Tables 5 and 6 and Fig. 2 examine the effects of increasing amounts of sand and gravel on water stability. Soils nearly devoid of gravel and coarse sand were unstable; the most stable group had 10–15% of particles in the 6–0·2 mm range, and the least stable had half or more in this fraction. A quarter of the soils had more than 2% carbon; as a group, these were very stable, and the mechanical composition had little effect (Fig. 2b). Table 6 includes fine sand (0·2–0·02 mm) in the 'coarse' fraction. The general increase in stability with diminishing proportions of coarse particles (6–0·02 mm) is still clear, but including fine sand diminishes contrasts between groups of soils (Fig. 2a). This suggests that the division between coarse and fine sand has important effects on stability; small proportions of fine sand tend to behave as silt and clay but when fine sand is a major fraction, soils are less stable. However, the correlation coefficients in Table 8 suggest that instability of arable soils is better related to amount of coarse particles, including fine sand, than to the 6–0·2 mm fraction alone. In the 'grassland' soil group, including fine sand had little effect. Organic carbon (and total N) and clay content were also well related to stability of the arable soils to water, but relationships were less in grassland soils (Tables 8 and 9). Per cent silt was nearly as important as % clay in making aggregates more stable (Table 8). Amount of coarse organic matter (i.e. recent remains of plants or organic manures) was related to stability, especially of grassland soils.

Linear regression coefficients (Table 9) show that about a third of the total variance in water instability of arable soils was associated with clay contents, but much less for the grassland soils. More than 40% of variance in the instability of arable soils was associated

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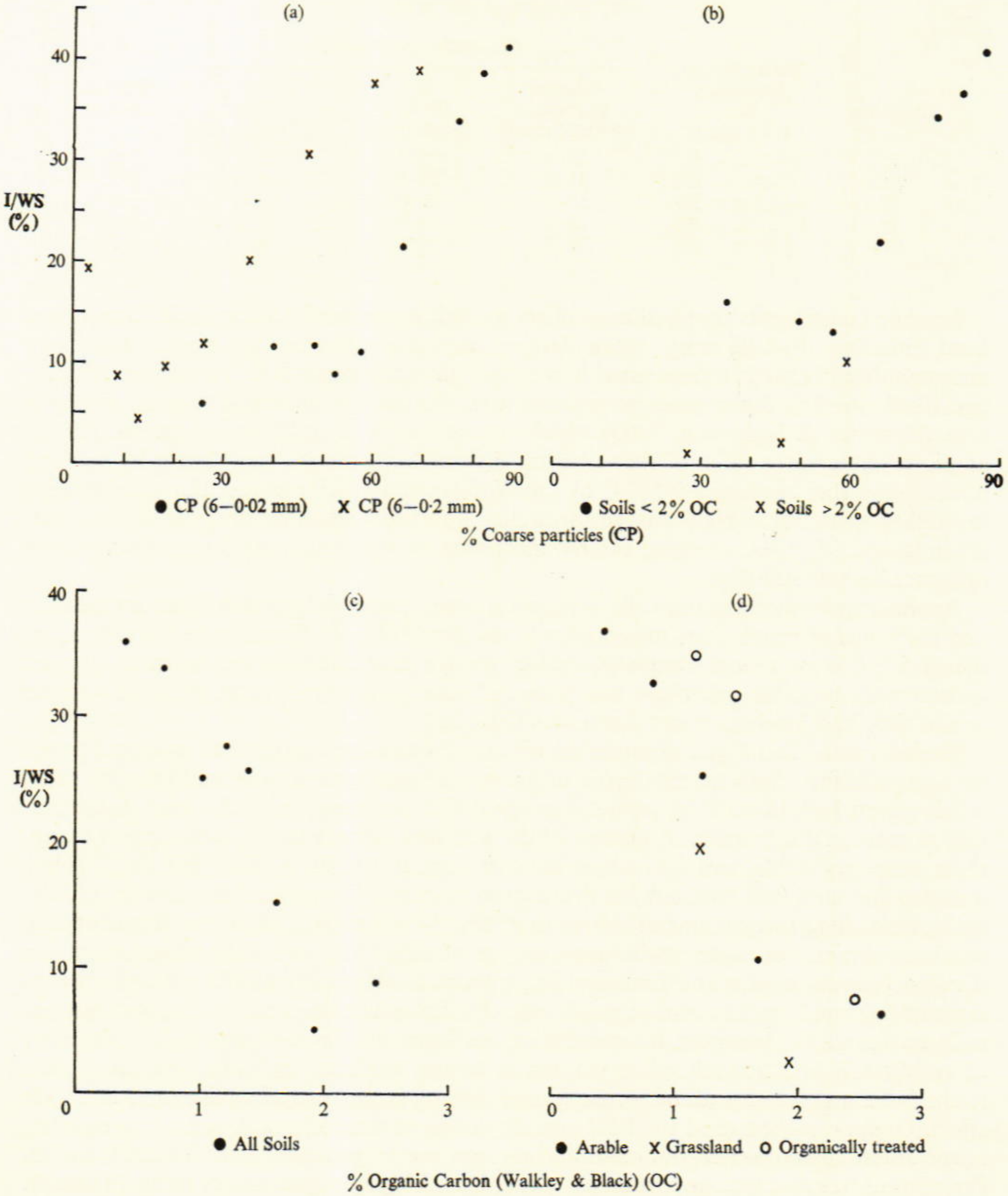

Fig. 2. The effect of soil composition upon the water slaking instability of 4–6 mm aggregates.

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with organic carbon, the proportion was less for grassland soils; %N was better related to instability than %C by the Walkley-Black method. Although the percentage of 'coarse' (2–6 mm) organic matter was significantly related to stability, the general relationship was poor.

The damage that wetting does to soil structure is related to the blocking of remaining pores by fine particles released by initial slaking. The movement of sand released in the instability test was observed through a hand lens while the aggregates in the glass tubes were being immersed; Table 12 summarises the information gathered. Ten categories of instability were gauged by the intensity of the slaking and the extent to which slaked particles became detached from the aggregates and were resorted; resorting did not occur until 16–21% of pore space was lost on water slaking. Field soils are also exposed to the kinetic energy of falling raindrops. Soils in which particles move and with instabilities exceeding 15%, are likely to 'cap' in rain by surface pores becoming blocked by mobile particles. It is difficult to gauge instability visually, because some soils swell rapidly on wetting but the partially-slaked fragments cohere. However, observing slaking of aggregates under a low power microscope was useful for grading the instability of very small samples or individual aggregates.

TABLE 12

Per cent water slaking instability and associated visual slaking appearance

Observed		Associated mean I/WS	Associated % coarse particles (6–0·02 mm)	Associated % organic carbon (W & B)	Empirical stability scale
Slaking	Resorting				
None	None	0·2	54·5	3·23	Very stable
Slight	None	1·4	48·8	2·32	Stable
Moderate	None	8·3	52·1	1·91	Slightly unstable
	Very small	16·0	55·2	1·73	
	Small	21·9	63·3	1·41	
Much	None	24·9	61·5	1·26	Moderately unstable to unstable
	Very small	26·6	65·0	1·39	
	Small	31·7	65·4	1·06	
	Much	41·7	66·7	1·02	
Complete	Complete	46·9	76·5	0·70	Very unstable

Dry slaking by mechanical pressure (I/DS). The dry slaking test, in which dry aggregated soil is compressed in a tube (with a pressure of 7 kg/cm^2), simulates the damage caused by pressure from tractor and other wheels, or soil-working tools (which also smear the soil). The values reported are the percentage diminutions in total pore space. Water slaking and dry mechanical slaking were related, though not very closely ($r = 0{\cdot}70$ for arable soils, 0·38 for grassland soils). Instability diminished with increasing organic matter content (Table 7 and Fig. 3) though organic matter had much less effect on stability than on water slaking. Arable soils in the group richest in organic matter were nearly twice as stable as those with least (Table 7). Loss of pore space in the test increased with increasing percentages of coarse material in the soils; losses were more than twice as great in the group of soils with most coarse particles as in the group with least (Table 6). These relationships were more evident when fine sand was included in the coarse fraction of soil (Tables 5 and 6 and Fig. 3a).

Soils rich in organic matter were nearly as much affected by compression as were those with little organic matter (Fig. 3d). The close relationship between diminishing resistance

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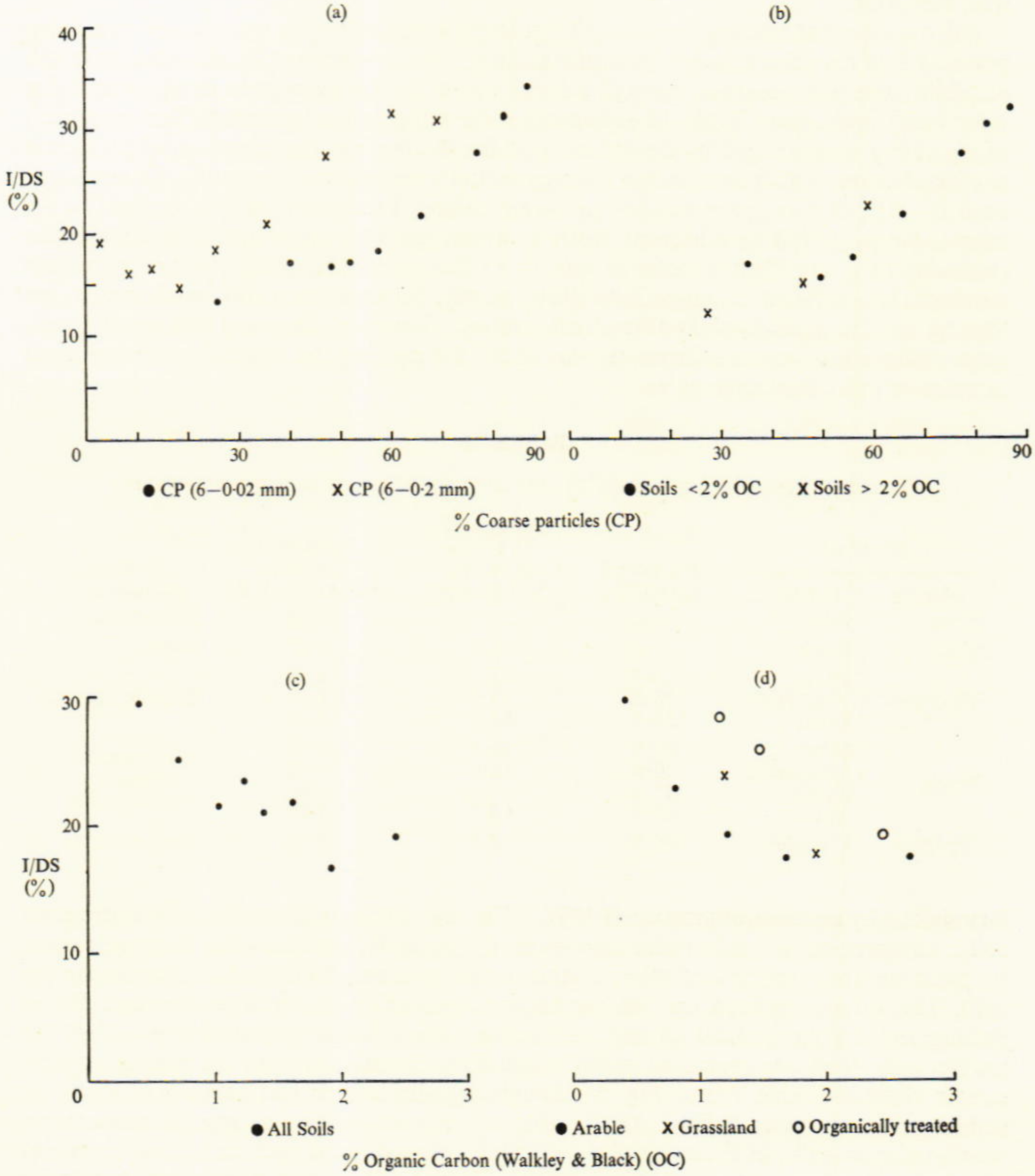

Fig. 3. The effect of soil composition upon the dry mechanical slaking of 4–6 mm aggregates.

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of air-dried aggregates to mechanical force and increasing amounts of coarse mineral fractions is illustrated well in Table 8, which shows little difference between groups of arable and grassland soils. The form or amount of organic matter had much less effect on mechanical resistance than on water slaking. Clay and silt had larger effects than organic matter in making aggregates stronger in the arable soils, and were even more effective in the grassland soils; both fractions had much less effect than coarse particles. Linear regression coefficients in Table 9 summarise these effects numerically. Tables 8 and 9 both show that the percentage of nitrogen was better related to the effects of dry mechanical slaking than % organic carbon, although %N only accounted for 20% of the variance.

Total mechanical slaking (I/MS). Results of this test, which measured the combined effects of water and mechanical slaking, indicate how damaging traffic over, or cultivation of, wet soils can be. Losses in pore space always exceeded those by water or dry mechanical slaking alone (Table 3). Even large increases in organic matter had only small effects on the stability of aggregates of arable soils; the organic matter in grassland soils had larger effects (Table 7). All the groups of soils resisted compression less as the proportions of coarse mineral particles increased (Tables 5 and 6 and Fig. 4). The relationship of proportion of coarse particles with total instability was altered little by including or omitting fine sand from the fraction (Fig. 4a and Tables 8 and 9). Organic matter (and % total N) had much larger effects on strength of aggregates from grassland than on those from arable soils (Tables 8 and 9 and Fig. 4d). Increasing organic matter (and total N) were associated with stronger aggregates from grassland soils, but less closely for aggregates from arable soils (Table 8). Indeed, Fig. 4d shows that the arable soils given organic manures were compressed much more easily than those not so manured.

Measurements on the cylinders of soil remaining after mechanical compaction showed that 95% of the arable soils had been compressed to at least 90% of the maximum depth possible; only a fifth of the grassland soils were compressed as much, as the lower ends of the cylinders were only slightly compacted. In two-thirds of the grassland soils the cylinders formed retained at least 30% of their volume in an uncompacted state. The roots left by grassland have a specific effect in helping soils resist damage by water and pressure; this effect was not achieved in the arable soils by organic manuring that had increased % organic carbon but not the coarse organic matter.

Breaking strength (BS). Clods are formed by cultivating heavy soil when it is so wet that the soil mass is compressed and smeared instead of being broken. It is important that any clods formed should be broken easily and the breaking strength test was developed to see how easily damage to structure caused by compressing wet soil could be repaired. The soil cylinders from the combined slaking and compression test were air-dried, a 25 mm section taken, and the force needed to split it under standard conditions measured.

Cylinders formed from the arable soils were mostly stronger than those from grassland; strength diminished rapidly as the proportions of coarse material in the soils increased (Tables 5 and 6 and Figs. 5a and 5b). There was no clear relationship between organic carbon content and breaking strength of cylinders for the whole group of soils (Table 7 and Fig. 5c). Dividing the soils into groups with more or less than 2% organic carbon, showed how the factors interacted. For any mechanical composition of soil, decreasing organic matter was associated with stronger cylinders (Fig. 5b). (In addition % clay and % organic carbon tended to increase together.) Fig. 5d divides the soils into groups with

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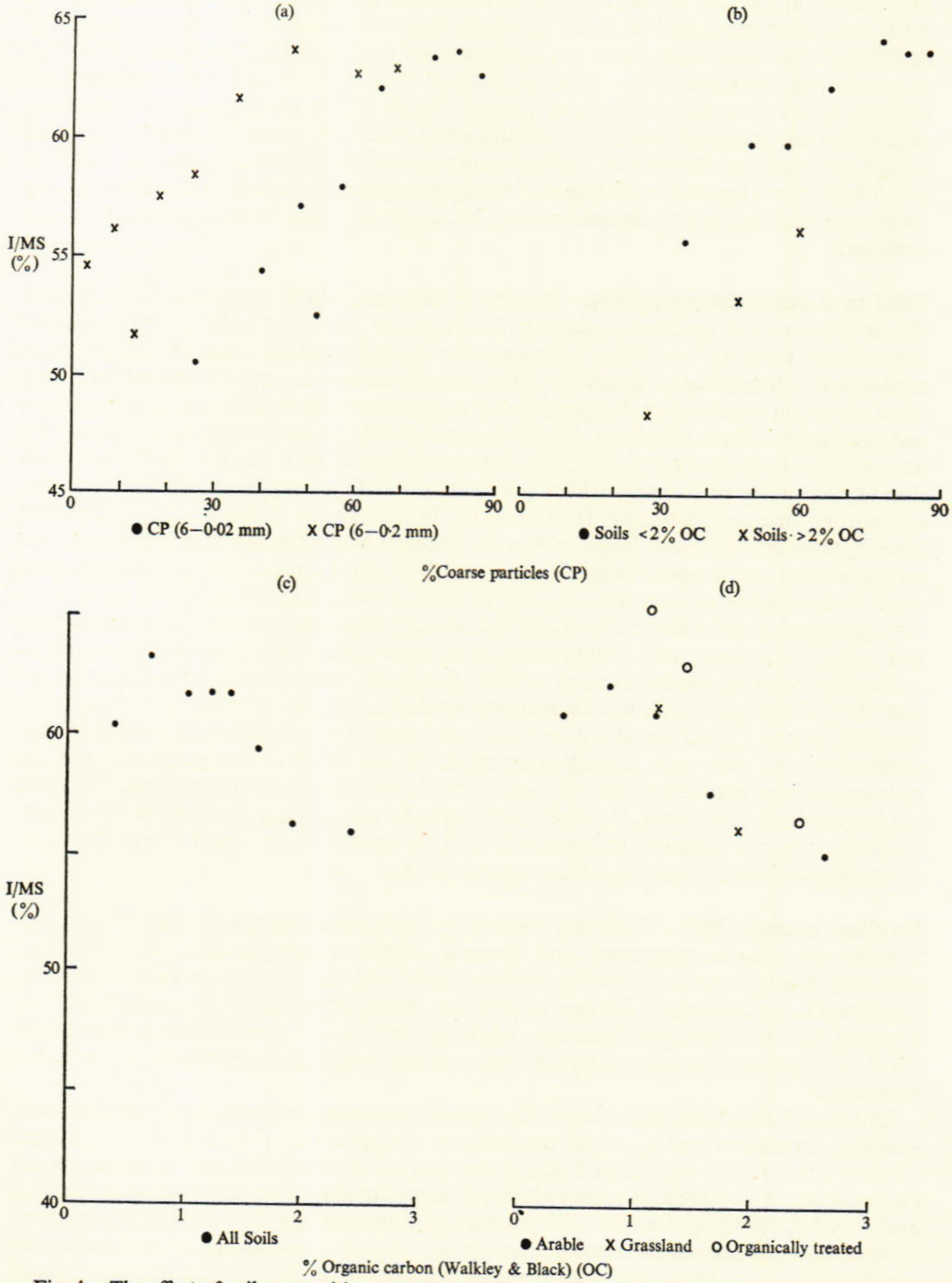

Fig. 4. The effect of soil composition upon the total mechanical slaking of 4–6 mm aggregates.

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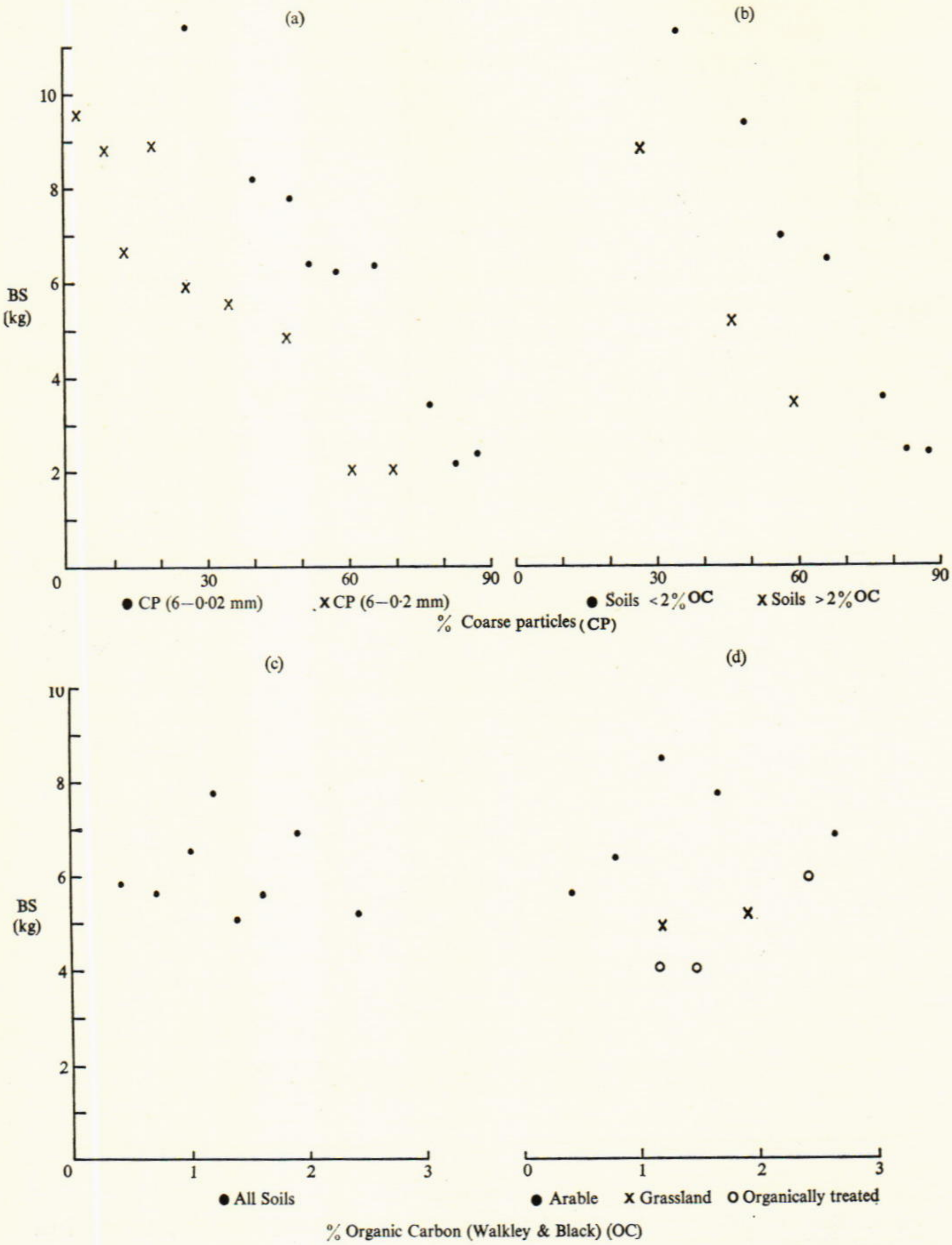

Fig. 5. The effect of soil composition upon the breaking strength of soil cylinders.

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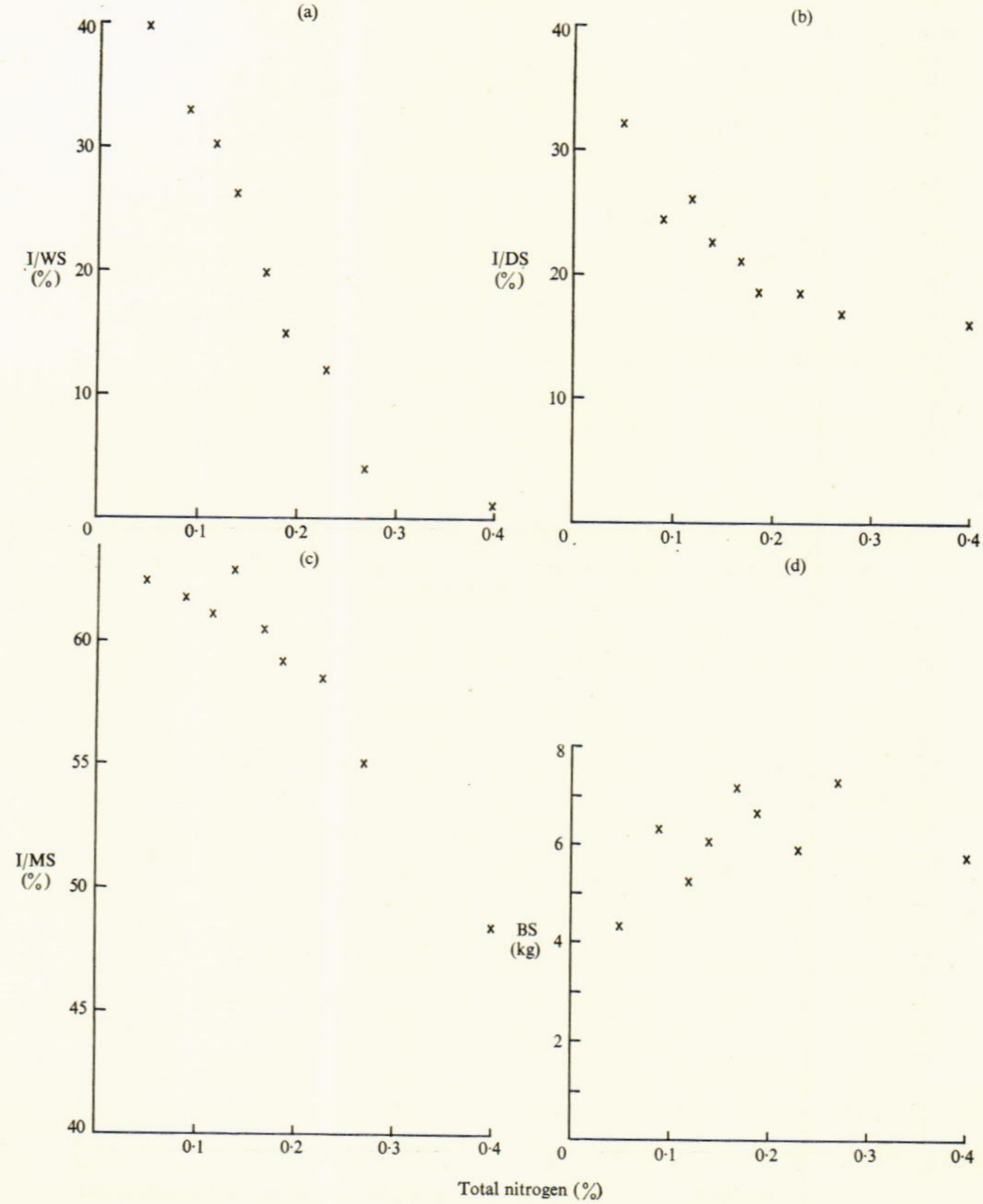

Fig. 6. The effect of percentage of total nitrogen upon water slaking instability, dry and total mechanical slaking, and breaking strength of soil cylinders.

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contrasted histories. Arable soils were strongest with about 1·2% carbon; grassland soils were usually less strong, and their strength diminished slightly with increasing carbon content. Increases in clay content made both arable and grassland soils much stronger (Table 8).

Relationships of soil nitrogen with results of physical tests. Unexpectedly, %N in soil was better correlated with results of many of the physical tests than was % organic carbon measured by the Walkley-Black method. Figure 6 shows relationships between % total N in the soils and the three measurements of instability and the one of strength of soils.

Instability in water was roughly linearly related to nitrogen content in the range 0·28–0·05% N (Fig. 6a); the relationship with % organic carbon (Fig. 2c) was of the same form, but less precise than with %N. The loss in pore space on dry mechanical slaking was also better related to %N than to % carbon, as also was total mechanical slaking (compare Figs. 4c and 6c). Neither carbon nor nitrogen contents were significantly related to the breaking strengths of soil cylinders. The scatter of points in the plot with organic carbon (Fig. 5c) indicates no relationship at all with breaking strength; Fig. 6d suggests, that, as %N increases, so does soil strength.

Per cent N seems to be better related than contents of organic carbon to the organic matter fraction that is active in stabilising soil structure: %N is easily determined and should be used in work that relates soil physical properties to organic matter contents.

Effects of interactions of soil properties on results of the physical tests

The results of the physical tests were rarely influenced by one factor alone. The commonest combination of properties acting together was percentage of coarse particles and percentage of organic matter, but clay content also interacted with other properties. The interactions of mechanical composition and organic matter content are complex and differ greatly from soil to soil. Correlation and regression analyses summarised in Tables 8 and 9 were used to select soil composition variates for partial regression analyses. Very many analyses were made, and those that removed the most variance are summarised here.

For the soils as a whole the partial regressions calculated removed half to two-thirds of the variance. Combinations of % coarse particles (6–0·02 mm) with % organic carbon removed about three-quarters of the variance in the water slaking and dry slaking tests on arable soils but were less successful on grassland soils. None of the variates examined explained total instability (mechanical + water slaking) of arable soils, but %N alone accounted for three-quarters of the variance in grassland soils. Combinations of % coarse particles plus a measure of the organic matter accounted for about two-thirds of the variance in breaking strength of soil cylinders and were roughly equally successful with arable and grassland; 'organic matter' was best measured by % total N.

Variations in bulk densities of the arable soils were not easily accounted for by regressions involving mechanical composition and organic matter, but %N and %C accounted for two-thirds of the variance in grassland soils. There were similar relationships in partial regression analyses involving water-holding capacity; mechanical composition and organic matter could account for about half of the variance in arable soils but 80% of the variance in WHC of grassland soils was accounted for by changes in contents of total N.

The more basic physical properties measured on the <2 mm soil aggregates—bulk density and water-holding capacity—were best characterised by soil organic matter;

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the coarse mineral fractions were less important. All the other measurements on arable soils involved tests on 4–6 mm aggregates that deformed the soil; successful partial regressions involved both coarse particles (6–0·02 mm) and organic matter; clay and silt were usually unimportant.

Partial regression analyses on two soil properties

Partial regression analyses were made on the results of the physical tests and soil properties; equations accounting for the largest percentage of variance associated with each test were calculated in terms of the amounts of coarse and fine material in the mineral fraction and amounts of organic matter. Table 13 gives the percentages of total variance that were accounted for by each of the regressions.

TABLE 13

Partition of variance in physical measurements by partial regressions on soil composition

Variates	CP —	Silt —	Clay —	OC —	N —	CP OC	CP N	Silt OC	Silt N	Clay OC	Clay N
					Water slaking instability (I/WS)						
Arable	64	30	38	41	45	71	70	56	57	59	59
Grass	23	10	(7)	23	28	(28)	(29)	(24)	(27)	29	(30)
All	51	23	30	40	46	61	61	49	52	55	56
					Dry slaking instability (I/DS)						
Arable	69	41	40	12	21	(70)	(69)	44	47	41	44
Grass	65	45	54	(7)	20	69	(66)	(43)	(45)	60	62
All	61	35	37	12	23	(62)	(61)	38	42	41	44
					Total mechanical slaking (I/MS)						
Arable	32	12	23	19	19	35	(33)	24	23	31	29
Grass	36	22	(0)	64	73	(66)	(72)	(67)	(73)	(64)	(73)
All	33	14	15	39	39	48	45	42	42	44	42
					Breaking strength (BS)						
Arable	53	21	48	(0)	(2)	67	65	(22)	(21)	52	50
Grass	11	10	35	9	(5)	57	67	36	36	48	53
All	37	16	39	(1)	(0)	63	62	22	19	47	46
					Bulk density (< 2 mm soil) (BD)						
Arable	17	14	2	34	38	36	(38)	39	40	(34)	38
Grass	15	(5)	(0)	69	56	(69)	(58)	(68)	(57)	(69)	61
All	19	13	2	49	48	(50)	(48)	51	49	(49)	49
					Water holding capacity (< 2 mm soil) (WHC)						
Arable	39	13	27	42	44	53	52	44	45	51	51
Grass	30	9	(0)	74	80	(74)	(80)	(73)	(81)	(75)	(79)
All	37	11	21	55	58	62	62	56	(58)	63	62

CP = % Coarse particles (6–0·02 mm)
OC = % Organic carbon (Walkley & Black)
N = % Total nitrogen
Silt = % Silt (0·02–0·002 mm)
Clay = % Clay (< 0·002 mm)
( ) = Regression not significant

The analyses included comparisons of the coarse soil fraction expressed as gravel + coarse + fine sand (6–0·02 mm) and with the coarse fraction omitting fine sand. The wider range (6–0·02 mm) was always more closely related for arable soils and results for gravel + coarse sand (i.e. 6–0·2 mm) are not given in Table 13 or discussed further except in connection with equations for bulk density and water slaking. Per cent organic carbon and %N were roughly interchangeable as measures of active organic matter in the soils.

https://doi.org/10.23637/ERADOC-1-5

Of all the factors examined 'coarse organic matter' (separated mechanically from the soils) in the range 2–6 mm, was least associated with the results of the tests on the soils. It had little or no relationship to results of the tests on dry slaking and total slaking, or on breaking strength of soil cylinders. Measurements of coarse organic matter were associated with 7% of variance in water-slaking tests on arable soil and with 16% for the grassland soils, much less than for other properties measured. The results of regression analyses involving coarse organic matter are therefore not included in Table 13. The contents of both silt and clay were included in the regressions. Per cent clay had important effects in many of the equations. Results with % silt were much less useful; the fraction rarely had an independent part, often it behaved as clay but was less well correlated with the results of physical tests, and sometimes it seemed nearly inert. Some results of equations including silt are in Table 13, but they are not discussed in detail. Effects of single soil properties and combinations of two properties are discussed below for each of the measurements. Regression equations are stated, together with the standard errors of their components, the residual mean squares, and the percentage of variance accounted for by regression. Three groups of 13 arable, grassland and 'mixed' soils, selected to give the widest range of coarse particles (6–0·02 mm), were used to test by substitution in the equations in the following sections:

Bulk density (BD)

Arable soils. Organic matter content (%C or %N) accounted for a third of the variance and there was only little improvement by taking account of the coarse or fine mineral fraction. The linear regression accounting for 38% of the variance was:

$$\text{BD (g/ml)} = 1{\cdot}42\ (\pm 0{\cdot}017) - 0{\cdot}78\ (\pm 0{\cdot}083)\ (\%\ \text{Total N})$$

Residual mean square 0·008 (145 d.f.).
For arable soils the mean bulk density calculated was 1·25 and 1·26 found. (Coarse organic matter accounted for 11% of variance.)

Grassland soils. Organic carbon accounted for 69% of variance; the best equation was:

$$\text{BD (g/ml)} = 1{\cdot}37\ (\pm 0{\cdot}025) - 0{\cdot}076\ (\pm 0{\cdot}008)\ \%\text{OC}$$

Residual mean square 0·005 (35 d.f.).
The mean bulk density for grassland soils was calculated as 1·16 against a mean of 1·14 found. There was no improvement for grassland soils from regression analyses incorporating the mineral fractions, but coarse matter alone was associated with 36% of the variance.

All soils. The proportions of coarse particles were associated with a fifth of the variance and organic matter with half; clay was not related (there was some relationship with % silt). Constants in the regression equations with organic matter and coarse particles as single factors are in Table 9; the best equation for the whole group of soils involved coarse particles (CP) gravel + coarse sand (6–0·2) mm, and organic carbon and associated with 52% of the variance, was:

$$\text{BD (g/ml)} = 1{\cdot}360\ (\pm 0{\cdot}18) + 0{\cdot}001\ (\pm 0{\cdot}0003)\ \%\text{CP}\ (6\text{–}0{\cdot}2\ \text{mm}) - 0{\cdot}076\ (\pm 0{\cdot}0065)\ \%\text{OC}$$

Residual mean square 0·008 (186 d.f.).

https://doi.org/10.23637/ERADOC-1-5

Average calculated and measured bulk densities for all soils examined were the same, 1·28.

Water holding capacity (WHC)

Arable soils. About 40% of the variance in water holding capacities of the arable soils was associated with the coarse fraction of the soils and 40–50% with the organic matter content. Per cent OC and %N were associated with about three-quarters of the variance for grassland soils. Clay accounted for a quarter of the variance for arable soils and was not associated with variance in the grassland soils. Silt accounted for an eighth or less of the variance in the whole group of soils. Combinations of organic carbon and either coarse particles or clay accounted for about half of the total variance.

The best equation (associated with 53% of the variance) was:

$$\%\mathrm{WHC} = 53{\cdot}2\ (\pm 4{\cdot}31) - 0{\cdot}30\ (\pm 0{\cdot}049)\ \%\mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) + 7{\cdot}93\ (\pm 1{\cdot}18)\ \%\mathrm{OC}$$

Residual mean square 103·8 (144 d.f.).
Average WHC calculated from the equation was 51·0% (against 46·1% measured).

Grassland soils. Organic matter (expressed as %N) accounted for the 80% of the variance; the equation was:

$$\%\mathrm{WHC} = 24{\cdot}2\ (\pm 3{\cdot}31) + 129{\cdot}8\ (\pm 10{\cdot}87)\%\ \mathrm{Total\ N}$$

Residual mean square 72·3 (35 d.f.).
The mean calculated value of WHC for the selected soils was 64·6% (against 67·6% measured). There was no improvement from taking account of the mineral fractions. Coarse particles accounted for a third of the variance, but clay for none.

All soils. Organic matter accounted for over half of the variance, smaller proportions being associated with % coarse particles or with % clay. The equation accounting for most (62%) variance was:

$$\%\mathrm{WHC} = 49{\cdot}2\ (\pm 3{\cdot}65) - 0{\cdot}26\ (\pm 0{\cdot}044)\%\ \mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) + 9{\cdot}27\ (\pm 0{\cdot}82)\%\ \mathrm{OC}$$

Residual mean square 104·6 (186 d.f.).
Using this equation to calculate WHC gave an average of 48·1% WHC, compared with the average of measured values 49·7% WHC.

An alternative, equally successful equation accounting for 63% variance, included the clay fraction (which, of course, increases as coarse particles diminish):

$$\%\mathrm{WHC} = 24{\cdot}2\ (\pm 1{\cdot}63) + 10{\cdot}55\ (\pm 0{\cdot}73)\%\ \mathrm{OC} + 0{\cdot}43\ (\pm 0{\cdot}07)\%\ \mathrm{Clay}$$

Residual mean square 103·4 (186 d.f.).
Calculated average WHC was 48·5% (the average of measured values was 49·7%).

Water slaking (I/WS)

Arable soils. Two-thirds of the total variance in % loss in pore space on water slaking was associated with percentage of coarse particles. Clay was also associated with a third of the variance and organic matter with rather more. Regressions involving both coarse particles and organic matter accounted for 70% of the variance for arable soils.

Most variance (71%) for arable soils was removed by this equation:

$$\%\mathrm{I/WS} = 0{\cdot}49\ (\pm 3{\cdot}73) + 0{\cdot}52\ (\pm 0{\cdot}042)\%\ \mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) - 6{\cdot}34\ (\pm 1{\cdot}02)\%\ \mathrm{OC}$$

Residual mean square 77·6 (144 d.f.).

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Grassland soils. Only a quarter of the variance was accounted for by the coarse fraction (6–0·02 mm). Slightly more variance (38%) was removed by including % coarse particles (6–0·2 mm) with % total nitrogen. The best equation for grassland soils was:

$$\%\text{I/WS} = 12{\cdot}9\ (\pm 5{\cdot}53) + 0{\cdot}22\ (\pm 0{\cdot}086)\%\ \text{CP}\ (6\text{–}0{\cdot}2\ \text{mm}) - 39{\cdot}4\ (\pm 14{\cdot}33)\%\ \text{Total N}$$

Residual mean square 103·5 (34 d.f.).
The average calculated value of I/WS using the equation was 4·7% against 0·4% measured. This poor agreement, and the failure to remove more variance in water instability tests on grassland soils, are both explained by the difficulty with this slaking test of assessing very small losses in pore space in groups of soils that are very stable to water (but the alternative method of Williams (1963) does differentiate well between small instabilities).

All soils. Percentage of coarse particles and % organic carbon were both important; the best equation, accounting for over 60% of total variance, was:

$$\%\text{I/WS} = 2{\cdot}47\ (\pm 3{\cdot}85) + 0{\cdot}47\ (\pm 0{\cdot}047)\%\ \text{CP}\ (6\text{–}0{\cdot}02\ \text{mm}) - 5{\cdot}95\ (\pm 0{\cdot}87)\%\ \text{OC}$$

Residual mean square 116·4 (186 d.f.).
Using this equation gave an average of 19·5% I/WS (average of measured values was 19·0%).

Dry slaking (I/DS)

Arable soils. Variance in the pore loss on dry slaking was mostly accounted for by the proportions of coarse particles; the following equation accounted for 69% of the variance:

$$\%\text{I/DS} = 0{\cdot}71\ (\pm 1{\cdot}21) + 0{\cdot}34\ (\pm 0{\cdot}019)\%\ \text{CP}\ (6\text{–}0{\cdot}02\ \text{mm})$$

Residual mean square 20·7 (145 d.f.).
(The average calculated value of I/DS was 19·3% compared with 20·9% measured.) Relationships with % clay (and with % silt) were less close, also with organic matter.

Grassland soils. These soils behaved similarly. The following equation accounted for 69% of the variance:

$$\%\text{I/DS} = -\ 6{\cdot}79\ (\pm 3{\cdot}87) + 0{\cdot}43\ (\pm 0{\cdot}051)\%\ \text{CP}\ (6\text{–}0{\cdot}02\ \text{mm}) + 1{\cdot}25\ (\pm 0{\cdot}57)\%\ \text{OC}$$

Residual mean square 16·3 (34 d.f.).
The average calculated values of I/DS for grassland soils was 18·9% and the average measured was 19·9. Percentage of clay was associated with 54% of the variance, and % coarse particles with 65%; silt was less important.

All soils. Equations combining mineral composition with other factors in partial regressions analyses removed no more variance than percentage of coarse particles alone. The best relationship associated with 61% variance was:

$$\%\text{I/DS} = 1{\cdot}41\ (\pm 1{\cdot}22) + 0{\cdot}34\ (\pm 0{\cdot}019)\%\ \text{CP}\ (6\text{–}0{\cdot}02\ \text{mm})$$

Residual mean square 27·2 (187 d.f.).
Average I/DS calculated was 20·3%, average measured was 19·6%.

Total mechanical slaking (I/MS)

Arable soils. Coarse particles accounted for a third, clay for a quarter (silt was less important than clay) and organic matter for a fifth of the variance; there was little gain

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from regressions on more than one soil property. The most variance (35%) was accounted for by the equation:

$$\%\mathrm{I/MS} = 53{\cdot}5\ (\pm 2{\cdot}15) + 0{\cdot}15\ (\pm 0{\cdot}024)\ \%\ \mathrm{CP} - 1{\cdot}54\ (\pm 0{\cdot}59)\ \%\ \mathrm{OC}$$

Residual mean square 25·9 (144 d.f.).
(The average I/MS calculated was 59% compared with 63% measured.)

Grassland soils. Percentage of coarse particles accounted for a third, but organic carbon for two-thirds and %N for three-quarters of the variance in I/MS; regressions on the two properties together removed no more variance than organic matter alone. The best equation associated with 73% variance for grassland soils was:

$$\%\mathrm{I/MS} = 70{\cdot}7\ (\pm 1{\cdot}83) - 59{\cdot}8\ (\pm 6{\cdot}00)\ \%\ \mathrm{Total\ N}$$

Residual mean square 22·0 (35 d.f.).
(The calculated average I/MS was 52%, compared with 53% measured.)

All soils. Coarse particles and organic carbon each accounted for about a third of the variance, and about 10% more was accounted for by a regression on the two properties. The best equation used, which did not involve quadratic or logarithmic functions, accounted for 48% of the variance and was:

$$\%\mathrm{I/MS} = 56{\cdot}4\ (\pm 1{\cdot}90) + 0{\cdot}13\ (\pm 0{\cdot}023)\ \%\ \mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) - 3{\cdot}11\ (\pm 0{\cdot}43)\ \%\ \mathrm{OC}$$

Residual mean square 28·2 (186 d.f.).
(Average I/MS for the whole *group of soils* calculated from this equation was 59%, the measured value was 62%.)

Breaking strength (BS)

Arable soils. Percentage of coarse particles or % clay each accounted for about half of the total variance in breaking strength of soil cylinders (silt was much less important); none was accounted for by the organic matter, measured as %OC or %N. Regressions of % coarse particles and % organic carbon *together* removed two-thirds of the variance. The most successful equation for arable soils was:

$$\mathrm{BS\ (kgm)} = 22{\cdot}2\ (\pm 1{\cdot}05) - 0{\cdot}20\ (\pm 0{\cdot}012)\ \%\ \mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) - 2{\cdot}29\ (\pm 0{\cdot}29)\ \%\ \mathrm{OC}$$

Residual mean square 6·15 (144 d.f.).

Grassland soils. The soils behaved differently: % coarse particles (and % silt) and % organic carbon each alone accounted for 10% or less of the variance; % clay was associated with about a third of the total variance. Interaction effects were clearly shown in regression equations combining coarse particles and organic matter, which accounted for two-thirds of the variance (using %N to measure organic matter). More variance was also removed in equations involving clay with organic matter, but these were less successful than those including coarse particles. The best equation for the grassland soils associated with 67% variance was:

$$\mathrm{BS\ (kg)} = 22{\cdot}9\ (\pm 2{\cdot}16) - 0{\cdot}21\ (\pm 0{\cdot}026)\ \%\ \mathrm{CP}\ (6\text{–}0{\cdot}02\ \mathrm{mm}) - 24{\cdot}9\ (\pm 3{\cdot}22)\ \%\ \mathrm{Total\ N}$$

Residual mean square 3·18 (34 d.f.).
(The calculated average value was 4·3 kg, against 4·1 kg measured.)

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All soils. Regression on % coarse particles and % organic matter removed most (over 60%) of the total variance. As with the separate groups, there were large interactions between these soil composition variates:

$$\text{BS (kg)} = 22{\cdot}3\ (\pm 0{\cdot}94) - 0{\cdot}20\ (\pm 0{\cdot}011)\%\ \text{CP (6–0·02 mm)} - 2{\cdot}43\ (\pm 0{\cdot}21)\%\ \text{OC}$$

Residual mean square 6·92 (186 d.f.).
The average calculated value was 7·6 kg compared with 8·0 kg measured.

Regressions on more than two soil properties

Further regression analyses were made involving more than two soil properties and their logarithms and squares. Some of these equations accounted for more variance than partial regressions involving two properties, but most of the regressions were not significant ($P = 0{\cdot}05$) and are not discussed here. Table 14 lists results from some of the equations involving three variates and compares the variance removed with that accounted for in the simpler regressions. Although some of the more complicated regressions removed a little more variance than those with only one or two variates, the gain was not commensurate with the extra work. It seems possible to account for most of the variance in these physical tests on soil only where one soil property dominates the results, as where % coarse particles determines amounts of wet or dry slaking of arable soils, or where % organic matter determines water-holding capacity of grassland soils. It was rare for two contrasted properties considered together to account for *much* more variance in the physical measurements discussed here than each property considered separately; it was very rare to account for much more than three-quarters of the total variance. But the results of the regression analyses must be regarded as satisfactory when account is taken of the many factors that must contribute to variability in the results and which were not identified and measured.

Relevance of the results to practical problems

Kemper and Koch (1966) studied 519 soils from Western USA and Canada but used only one criterion of structural stability—the percentage of the soil retained on a sieve with 0·25 mm square openings when agitated under water in a standard way. (A correction was made for sand particles larger than 0·25 mm.) Aggregate stability was related to organic matter, clay, free iron oxide, and exchangeable sodium (the last was 'of little importance in the soils studied'). A regression equation involving all these factors accounted for 31% of total variance of aggregate stability. The most consistent correlation was with organic matter: clay was important only in well-mixed surface soils; free iron oxide was important in stability of subsoils, but was less important in cultivated topsoils. Increasing organic matter to more than 2% added little to stability of soil aggregates but with less than 1% stability decreased rapidly.

Kemper and Koch reviewed the literature on aggregate stability in relation to soil structure. Wherever conditions are comparable, my results obtained on British soils fit those of Kemper and Koch and earlier workers. Large instability of pore space on water slaking is the reverse of large aggregate stability; measurements of both show the importance of organic matter content, but my work also shows that the amount of gravel + coarse sand + fine sand is even more important than organic matter in arable soils. The aggregates usually stable in wet sieving tests are much smaller units of the structure than the assembly of crumbs and other particles that make up cultivated land

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TABLE 14

Comparisons of variance associated with regressions of soil physical tests upon soil composition involving one, two or more independent variates

	% Variance accounted for		
	Arable soils	Grassland soils	All soils
Bulk density (BD)			
%N	38	56	48
%OC	34	69	49
%N, % Clay	38	61	49
%CP, %OC, $(\%CP)^2$	39	(72)	52
% Clay, Log %OC, $(\% Clay)^2$	(36)	85	(48)
%CP, Log %OC, $(\%CP)^2$	40	(79)	50
Water holding capacity (WHC)			
%N	44	80	58
%N, %OC	53	(74)	62
%CP, %OC, $(\%CP)^2$	57	(73)	64
% Clay, Log %N	50	86	57
Water slaking instability (I/WS)			
%CP	64	23	51
%N	45	28	46
%CP, %OC	71	(28)	61
%CP, %OC, $(\%CP)^2$	73	45	64
%CP, %N, Log %CP	71	46	63
%CP, %OC, $(\%CP)^2$, $(\%OC)^2$	(73)	(49)	67
Dry slaking instability (I/DS)			
%CP	69	65	61
%CP, %OC	(70)	69	(62)
%CP, Log %CP	73	69	64
%CP, %OC, $(\%CP)^2$	76	(71)	(66)
Total mechanical slaking (I/MS)			
%CP	32	36	33
%N	19	73	39
%CP, %OC	35	(66)	48
%CP, %OC, $(\%OC)^2$	(35)	(66)	49
Breaking strength (BS)			
%CP	53	11	37
%Clay	48	35	39
%CP, %OC	67	57	63
%CP, %N	65	67	62
%CP, %OC, $(\%OC)^2$	(67)	62	64
%CP, Log %N	63	67	59

CP = % Coarse particles (6–0·02 mm)
OC = % Organic carbon (Walkley & Black)
N = % Total N
Clay = % Clay (< 0·002 mm)
( ) = Regression not significant

usually described as having good tilth. They are also much smaller than the structural units in subsoils. Aggregates that are very stable in water usually have 'skins' of clay, or are cemented by iron oxides or organic matter. For these reasons, Kemper and Koch found that both organic matter and iron oxide had greater power to bind aggregates in subsoils than in cultivated surface soils. Aggregates in sub-surface layers result from pedogenic processes, whereas aggregates in cultivated topsoils largely depend on farming systems and cultivations and their stability depends greatly on both clay content and organic matter. Therefore a subsoil may contain a larger proportion of aggregates stable to wet sieving, provided the processes that developed it encouraged the subsoil to accumulate organic matter and to form stable ferric oxide bridges and cements binding particles

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together. This, of course, implies that the plant community under which the soil developed was deep rooting (to provide organic residues) and that the soil was well drained (to permit both deep rooting and the aerobic conditions in which ferric oxides are stable).

The aggregates that are stable to wet sieving are probably permanent units of the soil structure and may be of more direct use in pedological investigations than in planning arable farming. The aggregates used in this work are much more closely related to the assembly of particles that make up the structure and tilth thought important for crop growth. They are transitory and are formed when the weakest mechanical links in larger soil structures are broken by the forces exerted by freezing, by wetting and drying, or by cultivations. The best measure of structure that affects crop production is probably the amount of stable pore space expressed by capacity to hold water in the field; with this definition good structure implies an assembly of small, medium and large pores that, while permitting rapid drainage, nevertheless holds much water at relatively low tension.

The tests used were devised to assess soil characteristics important in planning land use, especially for arable farming and they are commended to investigators who advise farmers; they should also be useful measurements for making practical use of soil surveys. The methods are empirical, but so then are the conditions chosen for wet sieving tests of aggregate stability. Bulk densities and laboratory assessments of water holding capacities are easily measured; they are basic properties of the soils. The other tests were 'purpose designed'. Wet slaking shows whether soils will retain the good tilth established by suitable cultivation during spring or whether the structure collapses to a mass of soil with no macrostructure and having minimum pore space when saturated with water. Dry slaking shows how easily soil could be damaged by cultivations when it is dry enough to carry tractors. Total slaking shows the soil properties that make for resistance, or the lack of it, to compression by tractors and other implements used when soil is saturated with water. Compression caused by ploughing, or cultivating wet soil, or by traffic, is remedied when clods are easily broken; the 'breaking strength' test examines this possibility.

The results of all the tests are related to easily measured soil properties and are associated with mechanical analyses and organic matter contents by the simple equations listed. These may be used confidently to extend this work to other British soils and as an aid in forecasting behaviour when soils are cultivated. Reasons for having confidence in the relationships established are the close agreements between averages of measured properties and average values calculated from equations, and by the large percentage of the total variance accounted for in many of the regressions. When the soils used by Kemper and Koch were divided into 'surface cultivated layers', 'surface sod layers' and 'subsurface layers', regressions involving organic matter, clay and ferric oxide, accounted for 44, 35 and 38% respectively of the variance in aggregate stability. By contrast, several of the properties measured here were much more closely related to soil composition; it was common for 60% or more of the variance to be accounted for and some equations increased this to 75 or 80%.

The 'structure' of soils that affects crop growth has never been satisfactorily defined and it is improbable that any single laboratory test, or group of tests, can be devised to do so. Crop growth is altered both by pore space arrangements in topsoil and by the subsoil characteristics that govern drainage and root penetration. Ability to drain speedily so that aerobic conditions are quickly re-established after rain, together with capacity to retain much water at low tension, are probably the most important soil characters affecting yields in Britain. Arrangements of pores, cracks and channels that remove water

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quickly, also permit deep rooting and ensure that roots are not killed by water-logging. These conditions may also favour development of ferric oxide cements that bind particles into the kinds of aggregates found stable in wet sieving tests. A more complete assessment of the suitability of land for modern arable farming may be obtained by using the tests described here to assess top soil behaviour and a wet sieving test to assess the structure of subsoils.

Kemper and Koch (1966) showed the large effect that organic matter has on stability of aggregates in sub-surface layers, with improvements continuing up to 4% organic matter (few British subsoils in well-drained land have as much as 2%). The effects of free Fe_2O_3 were even more striking, with percentage aggregate stability increasing from 64% to 94% as free Fe_2O_3 increased from barely measurable to 2·5%; Fe_2O_3 cements had much more effect on stability of subsoils than of surface cultivated layers. It may be profitable to apply these concepts to assessing structure of British soil profiles. For example Broadbalk subsoil is stable and drains well. Kemper and Koch found this equation measured % stable aggregates in sub-surface layers.

$$AS = 65{\cdot}6 + 32{\cdot}8 \log \% OM - 0{\cdot}05\% \text{ clay} + 0{\cdot}008\% (\text{clay})^2 + 6\% Fe_2O_3$$

Applying this formula to values given by Avery and Bullock (1969) for Broadbalk subsoil 48–70 cm deep, suggested 84% of the aggregates were water stable. This value considerably exceeds the average aggregate stability (76%) of all the subsoils investigated by Kemper and Koch.

Summary and conclusions

Aggregates of 4–6 mm, prepared from 189 soils (mainly British) by deep freezing, thawing and air drying, were used in physical tests to relate soil composition with the instability of soil aggregates to water slaking, dry mechanical slaking and to combined wet and dry mechanical slaking. Breaking strength of compacted soil cylinders, bulk density and water holding capacity were also measured. There were 147 arable soils and 37 from grassland.

The water slaking test measured the stability of soil particles to capillary forces caused by water entering pores within air dried aggregates, and to the strains set up by hydration and swelling of clay and organic matter. Slaking was most influenced by content of coarse (6–0·02 mm) particles in soils containing less than 2% organic carbon. With more than 2% organic carbon (or 0·25% total nitrogen) the form of organic matter was important; grassland soils were more stable than arable soils, whose stability was little affected by organic manures. Soils with more than 70% coarse particles (6–0·02 mm) were very unstable, lacking clay and silt to bind the larger particles.

The dry slaking test measured the stability of air-dried soil particles to mechanical crushing. The results depended even more than those with water slaking on the amount of coarse mineral particles in the soil. The organic fraction of soil had much less effect and arable and grassland soils did not differ greatly. Organic manuring did not make soils more stable.

Total mechanical slaking measured the effect of mechanical compaction on soil that had been water slaked and then drained. The proportions of coarse mineral particles (6–0·02 mm) were most closely related to results of this test; clay, silt and coarse organic matter contents were not well related. Grassland soils were more resistant than arable

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soils to total slaking; %N was the best measure of their organic matter content for indicating stability.

Breaking strength measured the cohesion between particles of dried soil in a section of a cylinder formed by mechanical slaking when wet; this was air-dried before the test. The strength of the soil cylinders was more closely correlated with coarse particles (6–0·02 mm), and with % clay content, than with any of the measurements of organic matter. Both clay and silt contents were more closely related with breaking strength of cylinders from arable soils than from grassland.

Bulk density measured on <2 mm soil was more closely related to organic carbon (or nitrogen) contents, especially of grassland soils, than to coarse particles, clay or silt. The amount of 'coarse' organic matter, mostly undecomposed plant remains, was related to bulk density especially of grassland soils.

Water holding capacity of <2 mm soil was also more closely related to organic matter contents, especially of grassland soils, than to sand, silt, or clay fractions.

The soils used differed considerably in calcium carbonate contents, but there was no detectable association between this fraction and the physical properties measured.

The apparatus used was simple enough for routine measurements on soils; it could be further mechanised and the ancillary chemical analyses automated.

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References

Avery, B. W. & Bullock, P. (1969) The soils of Broadbalk; morphology and classification of Broadbalk soils. *Rep. Rothamsted exp. Stn for 1968*, Pt. 2, 63–81.

Bremner, J. M. (1960) Determination of nitrogen in soil by the Kjeldahl method. *J. agric. Sci., Camb.* **55**, 11–33.

Bremner, J. M. & Jenkinson, D. S. (1960) I. Oxidation by dichromate of organic matter in soil and plant materials. *J. Soil Sci.* **11**, 394–402.

Bremner, J. M. & Jenkinson, D. S. (1960) II. Effect of carbonised materials. *J. Soil Sci.* **11**, 403–408.

British Standards Institution (London) (1948) Precipitated calcium carbonate. *Br. Stand.* No. 1460.

Kemper, W. D. & Koch, E. J. (1966) Aggregate stability of soils from Western USA and Canada. *Tech. Bull. U.S. Dep. Agric.* 1355.

Walkley, A. (1935) An examination of methods for determining organic carbon and nitrogen in soils. *J. agric. Sci. Camb.* **25**, 598–609.

Williams, D. E. (1948) Rapid manometric method for the determination of carbonates in soils. *Proc. Soil Sci. Soc. Am.* **13**, 127–129.

Williams, R. J. B. & Cooke, G. W. (1961) Manure, grass, and soil structure. *Soil Sci.* **92**, 30–39.

Williams, R. J. B. (1963) A new method for measuring soil stability. *Chemy Ind.* 1032–1033.

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