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Induration of ferrallitic microaggregated soils (Northeastern Brazil)
Induration de sols microagrégés ferrallitiques (Nord-est du Brésil)

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Studies of soils in the northeastern region of Brazil showed the widespread occurrence of hard subsurface horizons that strongly restrict the penetration of plant roots, water and ploughing tools, and that consequently reduce the agricultural yields. The objective was to characterise the groundmass of these hard horizons and to identify the cementing agent responsible for the hardness. Samples were collected from friable subsoil horizons which are latosolic horizons, and from hard subsoil horizons which are either *fragipã* or *duripã* according to the Brazilian soil classification. The mechanical stability of the groundmass was measured. Thin-sections were prepared and examined in scanning electron microscopy using backscattered electrons. The thin sections were also used for microprobe analysis.

The results showed a great stability of *fragipã* and *duripã* when they are shacked in water. This stability clearly indicated that they are indurated horizons and related to duripans. The results showed also that the groundmass of the indurated horizons differed from friable latosolic horizons by the continuity of the solid phase. The clayey material responsible for the continuity consisted mainly of kaolinite with small variation of the aluminium and iron contents. The difference of consistence between the non-indurated and indurated horizons would be related to an increase in the aluminium content and a decrease in the iron content. Thus, aluminium compounds would play a major role as cementing agent within the clayey material.

Key words: ferrallitic soils, duripan, microanalysis, iron, microaggregate, Brazil
Mots clés: sol ferrallitique, duripan, microanalyse, fer, microagrégation, Brésil

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Introduction

Studies of soils in the north-eastern region of Brazil showed the widespread occurrence of hard subsurface horizons that strongly restrict the penetration of plant roots, water and ploughing tools, and that consequently reduce the agricultural yields (Embrapa, 1975). Hard horizons are present in topographic depressions of coastal plateaux (Silva & Araujo Filho, 1989; Silva *et al.*, 1993). The objective of the present study was to characterise the groundmass of the hard horizons and friable latosolic horizons, the latter being closely associated with the hard horizons within the toposequences. The results enabled discussion of cementing agent responsible for induration within the studied soils and were compared with those earlier published by Silva *et al*. (1997).

Material and methods

Site

The site is near Boca da Mata, 50 km west of Maceió (Alagoas State). The climate is warm and humid with a mean annual air temperature of 25° C, a mean annual precipitation of 1640 mm and a mean annual evapotranspiration of 1450 mm. For 3-4 months, between October and January, rainfall can be smaller than 50 mm, i.e. much less than evapotranspiration. The landscape consists of plateaux (altitude of 120 m) which formed a discontinuous coastal band 15-75 km wide. The plateaux show numerous depressions variable in shape (depressions with or without outlet) and extension (from 5 m wide and 0.3 m deep to 3 km wide and 1 m deep). Originally, the plateaux were covered by dense forest; the deforestation process started about 300 years ago and the increasing of the sugar cane production aggravated the process in this century. Soils differentiated on the Barreira deposit (Kistler, 1954; Mabesoone & Alheiros, 1988). A soil survey of the site (Silva & Araujo Filho, 1989) showed that the soil cover consists mainly of *Podzólicos* and *Latossolos amarelos* (Embrapa, 1988; Oliveira *et al*., 1992) which are Ultisols and Oxisols, respectively (Soil Survey Staff, 1975). Soils exhibited friable subsoil horizons (latosolic horizons) excepted in the depressions where they exhibited hard subsoil horizons overlaying latosolic horizons. *Podzois*, which are Spodosols, occurred also locally in the centre of the largest depressions.

Field sampling

A trench, 50 m long and 3 m deep was excavated from the edge to the centre of a depression for a detailed field study (Boulet *et al*., 1998). The mineralogical composition consists invariably of kaolinite (about 85 %), quartz (about 10 %), iron oxi-hydroxides (about 4 %), anatase and zircon (about 1 %). The trench showed friable subsoil horizons, which are latosolic horizons (*L*), and hard subsoil horizons. The latter can be easily distinguished in the field by the lack of macroporosity and high strength. They can be sampled and broken only with difficulties under both wet and dry conditions. According to the Brazilian soil classification (Embrapa, 1988; Oliveira *et al*., 1992), two types of hard horizons were identified: (i) *fragipã (F)* which become softer after immersion and shaking in water, (ii) *duripã (D)* which are always very hard even when immersed and shacked in water. The trench showed lateral transition between *L, F* and *D* subsoil horizons. Undisturbed samples were collected from these subsoil horizons at about 1 m depth. Collection of undisturbed samples from the *F* and *D* horizons required a bell-shaped saw with carbide teeth.

Laboratory study

Aggregate stability tests were carried out in triplicate with air-dried samples 3-5 mm in diameter. The procedure (Le Bissonnais, 1996) consisted of submitting the samples to three different treatments of disaggregation: (i) fast wetting by immersion in distilled water, (ii) slow wetting by capillary rise, (iii) immersion in ethanol before immersion in distilled water and mechanical shaking. After sieving in ethanol, the amount of aggregates remaining on the 50, 100, 200, 500, 1000, 2000 µm sieves and the amount of < 50 µm material were determined for each treatment.

After impregnation of oriented and undisturbed samples, thin-sections were prepared following the method of Fitzpatrick (1984). The surfaces were polished and coated with carbon for examination in scanning electron microscopy using backscattered electrons (Bruand *et al*., 1996) and for electron microprobe analysis. Observations were carried out in scanning electron microscopy with a Cambridge 90B instrument (magnification from x 300 to 1500) using the backscattered electron emission.

Si, Al, Fe, Ti, Mn, K, Mg, Ca, Na, P, S and Cl contents were determined on the thin sections using a Camebax Datanim electron microprobe equipped with four wavelength-dispersive spectrometers (WDS) and linked with the ZAF-MBXCOR quantitative analysis software. The accelerating voltage was 15 kV, the probe current was 10 µA and the count time was 90-120 s. Chemical determinations concerned small areas (1-2 $µm^2$) or larger surfaces (25-50 $µm^2$).

Results and discussion

Mechanical stability of the groundmass fabric

Stability tests showed that for the *L* horizon, 15 % of the sample remains > 2 mm after the fast wetting treatment and 30 % after slow wetting or mechanical shaking treatment. The *F* and *D* horizons showed very high stability. For the *F* horizon, 74 % of the sample remains > 2 mm after the fast wetting treatment, 77 % after the slow wetting treatment and 87 % after the mechanical treatment. The stability was higher for the *D* horizon (87 to 95 % of the sample remain > 2 mm whatever the treatment). The < 2 mm material resulting from stability tests was mainly constituted of > 100 µm aggregates: only 10 % of the < 2 mm material was < 100 µm for the *L* horizon and about 2 % for the *F* and *D* horizons.

Field observations suggested that the *D* horizon differed from the *F* horizon by cementation because the *D* horizon were always very hard even when immersed and slacked in water. Laboratory results showed high variation of stability between friable and hard horizons and low variation of stability between the *F* and *D* horizons. This low variation would be related more to the degree of induration than to any difference of origin for the consistence: cemented for the *duripã* and uncemented for the *fragipã*.

Groundmass fabric

Thin section showed high proportion of clay in the groundmass of *L*, *F* and *D* horizons. The surface area occupied by clay and by coarse grains (both silt and sand) was about 35-45 % and 20-25 %, respectively. The coarse grains were mainly quartz, ranging from fine silt to coarse sand. They were well sorted and subangular to rounded grains.

Observations also revealed microaggregation of clay in the *L*, *F* and *D* horizons but it was more developed in the *L* horizon. The groundmass fabric of the latter was heterogeneous, mainly agglomeroplasmic, and secondarily porphyrosquelic (Brewer, 1964). The agglomeroplasmic fabric consisted of dense microaggregates (5-100 µm in diameter) which were composed of closely packed clay (with or without incorporated fine silt). Most voids were either packing voids (2-100 µm) between microaggregates or vughs (100-250 µm) although rare channels were also present. These voids were polyconcave and were well connected. Some of the microaggregates were coated and linked one together by clay material. The coatings and bridges (1-2 µm thick) differed from aggregates by their grey level on the backscattered electron scanning images (BESI). The aggregates were lighter than the coatings and bridges. The porphyrosquelic fabric showed microaggregates similar to those which were described for the agglomeroplasmic fabric, but they were very closely packed and embedded in a clay material which exhibited on the BESI a grey level darker than for the microaggregates. The porosity was lower than for the agglomeroplasmic fabric. The voids consisted of packing voids (2-20 µm) between microaggregates, vughs or channels (100-250 µm) and planar voids (10-20 µm in width). These voids varied in shape and were weakly connected. Clay-coatings and clay-bridges occurred also in some places.

The groundmass fabric of *F* and *D* horizons were also heterogeneous but mainly porphyrosquelic, and secondarily agglomeroplasmic. Thus, it was denser than for the *L* horizon. The surface area occupied by porphyrosquelic fabric was largely greater than in the *L* horizon. The amount of aggregates covered by clay coating and linked by clay-bridges was also greater for the agglomeroplasmic fabric. Consequently, the porosity was lower and the groundmass was more continuous in the *F* and *D* horizons than in the *L* horizon.

Finally, SEM observations showed that the *L*, *F* and *D* horizons have a microaggregated fabric but there is a gradient of continuity for the solid phase which increase from the *L* to the *F* horizons and from the latter to the *D* horizon. The continuity of the solid phase appeared in relation with the closed packing arrangement of the microaggregates and with the presence of clayey material covering and linking the microaggregates one together. This continuity and, consequently the low porosity (small voids weakly connected) could partly explain the hardness of the *F* and *D* horizons.

Chemical composition of the fine material

Results of microanalysis showed close composition of the clayey material between *L*, *F* and *D* horizons. The SiO_2 content (about 50.2 %) was similar for all the studied horizons. The small difference of composition between *L*, *F* and *D* horizons concerned the Al_2O_3 and Fe_2O_3 contents. The Al_2O_3 content increased from 42.6 % in the *L* horizon to 44.6 % in the *F* and *D* horizons. The Fe_2O_3 content decreased progressively from 4.8 % in the *L* horizon to 4.3 % in the *F* horizon and then 2.7 % in the *D* horizon. The Si/Al atomic ratio of the clayey material was about 1.01 in the *L* horizon and about 0.95 in the *F* and *D* horizons. The results were consistent with the homogeneous and dominantly kaolinic nature of the clayey material. These results confirmed that both a decrease in the Fe_2O_3 content and an increase in Al_2O_3 content play a major role in the induration process as earlier discussed by Silva *et al*. (1997).

Conclusion

Even if the hard *F* and *D* horizons presented differences of consistence in the field, the laboratory study with air-dried samples showed low variation of stability. Their great stability even when they are immersed and shacked in water show that they are indurated horizons and related to duripans.

The fabric appeared mainly porphyrosquelic in the *F* and *D* horizons and dominantly agglomeroplasmic in the *L* horizon. Thus the groundmass of the indurated horizons differed from those of the non-indurated horizon by the continuity of the solid phase.

The clayey material responsible for the continuity consisted mainly of kaolinite with small variation of the aluminium and iron contents. The difference of consistence between the non-indurated and indurated horizons would be related to an increase in the aluminium content and a decrease in the iron content. Thus, aluminium compounds would play a major role as cementing agent within the clayey material. The cementation would be closely associated with a decrease in the iron content, probably because of the dissolution of iron oxi-hydroxide including a high proportion of Fe-Al substitutions. This process would explain both the decreases in the Si/Al ratio and Fe content, which were associated to the induration process for the studied soil.

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