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Chemical stabilization of tropical soils: physical, chemical, mineralogical and microstructural characterization

Abstract. This paper reports the physical, chemical, mineralogical and microstructural characterization of three soils of the *Zona da Mata* of Minas Gerais State, Brazil, and their mixtures with the chemical stabilizer RBI Grade 81 for geotechnical engineering purposes. The investigation consisted of: (i) one mature residual soil (soil 1) and two less weathered soils (soils 2 and 3) on gneiss; (ii) stabilizer contents of 2%, 4% and 6% regarding soil dry weight; (iii) mixtures specimens cured during seven days in a conditioning chamber; (iv) soils and mixtures specimens compacted at the standard and modified Proctor compaction efforts, for microstructural characterization. The results indicated that the chemical stabilizer promoted considerable changes in all physical, chemical, mineralogical and microstructural properties of studied soils. There were observed changes in texture and plasticity, increases in pH and CEC and decreases in exchangeable acidity. Energy dispersive X-ray spectrometry (EDS) analyses indicated that contents of Si and Al oxides in soils decrease after chemical stabilization, probably by solubilization of these oxides and Ca silicates and aluminates formation during hydration and/or pozzolanic reactions of chemical stabilizer with soils. With reference to mineralogy, the chemical stabilizer addition resulted in peak reduction of all clay minerals and the formation of rankinite, a Ca-silicate in a well-crystalline form, easily identified by X-ray diffraction, strengthening the conclusions gotten from the EDS analyses. The microstructure of soils subjected to high compaction effort (modified Proctor) showed the development of microfractures and unconnected crack voids in soil 1, whereas in the sand soils 2 and 3 we also observed widespread break of quartz grains. The chemical stabilizer addition accounted for the formation of well-developed cementation nuclei, notably in soil 3 mixture.

Keywords: Tropical soils; Chemical stabilization; RBI Grade 81 stabilizer; Physical, chemical, mineralogical and microstructural characterization; Geotechnical applications.

7.1. Introduction

The perfecting of chemical stabilization techniques for tropical soils requires the development of extensive laboratory and field experimentation to attain the engineering standards to comply with the technical norms. Regarding laboratory programs, an important step to be executed is the characterization of the physical, chemical, mineralogical and microstructural characteristics of soils and their mixtures with the chemical additives used, thus creating essential parameters for a complete technical assessment, together with data on the mechanical strength and durability of the end product.

Thus the objective of this study was to widen the Brazilian databank on the physical, chemical, mineralogical and microstructural characteristics of soils stabilized chemically for geotechnical purposes, especially for highway applications. Three residual gneiss soils of the *Zona da Mata* of Minas Gerais State, Brazil, mixed with the RBI Grade 81 chemical stabilizer were characterized technologically.

RBI Grade 81 is chemical stabilizer commercialized by the Anyway Solid Environmental Solutions Ltd. Kerem Maharal Corporation for highway construction applications. In the last decade the product was recognized internationally as a highway pavement layers stabilizer, in the functions of improving the subgrade, sub-base, base and first cover, which has been applied in several countries on the African continent and in some countries in Europe, such as Portugal, Spain and Italy. It has been little used in Brazil and the only reference is the construction of the base layer of the service patio of the Vallourec & Mannesmann do Brazil S.A. Corporation in Belo Horizonte, Minas Gerais State, which showed promising results (LIMA et al., 2003). Regarding Laboratory studies on the Brazilian soils stabilized with RBI Grade 81, data recently presented in the studies by Caneschi et al. (2004), França (2003), Machado et al. (2001) and Trindade et al. (2005a, 2005b, 2005c, 2006a, 2006b, 2006c) showed that the product accounted for substantial improvements in the mechanical properties of different types of soils (ranging from highly plastic clays to sandy soils), but the most expressive mechanical strengths gains generally occurred in mixtures of the chemical additive with granular soils.

The following will be discussed as specific topics in the present study: (i) influence of the chemical additive content on the physical (Atterberg limits, grain size

distribution, grain unit weight), chemical (pH, cationic exchange capacity and potential acidity) and mineralogical soils properties; (ii) effects of applying different compaction efforts and the addition of chemical stabilizer on the microstructural characteristics of the soils using images obtained from optical microscope (OM) and secondary electron signals generated in a scanning electronic microscope (SEM); (iii) effects of the chemical stabilizer incorporation on chemical elements contents measured by energy dispersive X-ray spectrometry (EDS) analyses.

7.2. Materials and experimental methods

7.2.1. Materials

The present study was carried out on three tropical soils derived from Pre-Cambrian gneiss, forming a clay-sand-silt sample collected in the B horizon of a mature residual soil (soil 1), classified pedologically as Red-Yellow Latosol, and two sand-silt-clay samples collected in the C horizon from two young residual soils (soils 2 and 3). The soil stabilizing agent used was RBI Grade 81, at contents of 2%, 4% and 6% compared to the dry soil weight. Further information on the soils and the chemical stabilizer assessed in this study can be found in Trindade et al. (2006a, 2006b).

7.2.2. Methods

7.2.2.1. Soils sampling

The samples were collected with hand tools in cutting trenches, packed in 50 kg plastic bags and identified by labels containing the data on the soil origin. The bags were then taken to the Civil Engineering Laboratory (LEC) of the Civil Engineering Department (DEC) at the University of Federal University of Viçosa where they were air dried, broken up, sifted through a 4.8 mm mesh and placed in plastic bags for later use.

7.2.2.2. Physical and chemical characterization

The geotechnical characterization was carried out following the recommendations of the Brazilian Technical Standards Association (ABNT). The tests carried out were: (i) sieve analysis (ABNT, 1984d); (ii) determination of liquidity limit (ABNT, 1984a); (iii) determination of plasticity limit and plasticity index (ABNT, 1984c); and (iv) determination of grain unit weight (ABNT, 1984b).

The chemical analyses were performed according to the procedures of the Brazilian Agricultural Research Corporation (EMBRAPA, 1997), and the mean value of three determinations was considered for each analysis. The pH in H₂O was determined by a potentiometer, using proportions of 1:2.5 (volume/volume) soil:solution. The Ca²⁺ and Mg²⁺ exchangeable cations were extracted in KCl 1 mol/L and determined by atomic absorption spectrometry. The Al³⁺ cation, extracted by KCl 1 mol/L, was determined volumetrically by titrating with NaOH 0.025 mol/L. The potential acidity (H⁺ + Al³⁺) was determined by extraction with 0.5 mol/L calcium acetate at pH 7.0 and later titrating with NaOH. The K⁺ and Na⁺ cations were extracted by Mehlich-1 extractor and determined by flame photometry. The following were determined from the results of these analyses: (i) the sum of the exchangeable bases (SB): Ca + Mg + K + Na; (ii) cation exchange capacity (CEC): SB + (H + Al); and (iii) percentage base saturation (V%): $(SB / CEC) \times 100$.

The procedures recommended by the ABNT (1986a) were followed for the preparation of the disturbed samples for the laboratory tests, while the chemically stabilized soil samples used in the physical and chemical property characterization experiments were prepared according to the description in the following paragraphs.

The samples of each one of the soils were placed in 2 kg plastic bags to which the chemical additive was added in amounts of 2%, 4% and 6% content, then homogenized to incorporate it uniformly in the soils to maximize the occurrence of the soil additive reaction processes. Finally, each one of the samples received a quantity of water necessary to reach the optimum moisture contents determined in the compaction tests carried out at the Standard Proctor compaction effort. The plastic bags were sealed and placed in a moist chamber with relative air humidity greater than 95%, then starting the cure time of the mixtures. After seven-day cure time, the samples were air dried, broken up in a pestle with a hand mortar and sieved through a 2 mm mesh. The

hygroscopic moisture was determined in each one of the samples and experiments were performed to determine the physical and chemical properties.

7.2.2.3. Mineralogical characterization

The soil mineralogy (soils 1, 2 and 3, and adding mixture) was identified by X-ray diffractometry, using the two soils fractions separated by the 53 μm mesh. Powdered specimens from the $\geq 53 \mu\text{m}$ fraction were mounted in excavated glass slide, using neutral glue for fixing the sample, avoiding any orientation. Oriented samples were mounted with the $< 53 \mu\text{m}$ fraction of analyzed materials, allowing the settling of drops suspension onto a glass slide, followed by air-drying.

All samples were cobalt-irradiated (Co- $K\alpha$) in the 4° and 50° 2θ interval, using a X-ray diffractometer manufactured by Rigaku Radiation Shield Company set with a speed of $2^\circ 2\theta/\text{min}$, fitted with a nickel filter. Data acquisition was made automatically at each $0.05^\circ 2\theta$.

7.2.2.4. Microstructural characterization

The microstructural characterization was carried out by means of optical and scanning-electron microscopy and microanalysis, for soils samples 1, 2 and 3, as well as its mixtures with 6% of chemical stabilizer, which were previously cured for seven days in a wet chamber.

For thin sections prepared for optical microcopy, the following steps were considered: (i) the specimens were compacted in the optimum compaction parameters (w_{opt} and y_{dmax}) determined in the modified Proctor test (Table 7.2); (ii) mixture specimens were cured in an acclimatized room for a period of seven days and after cure time were oven-dried at 50°C for 24 hours; and (iii) after, specimens were impregnated with a resin mixture, using 450 mL of polyester resin, 550 mL styrene and 5 mL catalyser; polymerization was accomplished after 30 days in a ventilated room, followed by thin sectioning, using a diamond-powder polishing system. Thin sections were photographed in a Pentax camera fitted in a Olympus SZH binocular at plain light and magnified 15X. All microstructural descriptions followed the recommendations of Bullock et al. (1985).

With reference to SEM analyses, it was used small 1 cm³ compacted samples extracted from specimens compacted in the optimum parameters determined in compaction effort of standard and modified Proctor tests (Tables 7.1 and 7.2). It should be emphasized that the Brazilian standard and modified Proctor compaction tests are similar to the AASHTO standard and modified compaction tests. The samples were dried in a chamber at 50° C for 24 hours and fixed on aluminum stubs using double faced carbon adhesive tape. Next, a coating of approximately 20 nm of a palladium gold alloy was applied, using an FDU 010 model metalizer, manufactured by Balzers Inc., USA. The samples were observed under a VP 1430-type scanning electronic microscope, manufactured by LEO Electron Microscopy Oberkochen, Germany, that operated at 15 kV. The metalization and scanning electronic microscopy were both carried out at the Nucleus for Microscopic and Microanalysis (NMM) at the Federal University of Viçosa (UFV).

The compaction tests were carried out following the methodology recommended by the ABNT (1986b), compacting the mixtures for between two to four hours after adding the stabilizer, following the usual procedures for soil-cement and soil-lime mixtures. Tables 7.1 and 7.2 show the optimum moisture content values (w_{opt}) and maximum dry unit weight (γ_{dmax}) of the soils and their respective mixtures used in molding the specimens. Limits were fixed for specimen acceptance as proposed by the Brazilian National Highway Officials (DNER, 1994) in their preparation: maximum dry unit weight ± 0.30 kN/m³ and optimum moisture content $\pm 0.5\%$.

Table 7.1. Compaction test data: Standard Proctor (TRINDADE et al., 2006a)

Amount of RBI Grade 81 (%)	Soil 1		Soil 2		Soil 3	
	γ_{dmax} (kN/m ³)	w_{opt} (%)	γ_{dmax} (kN/m ³)	w_{opt} (%)	γ_{dmax} (kN/m ³)	w_{opt} (%)
0	13.85	30.78	15.07	17.98	17.71	13.11
6	13.64	32.70	14.81	20.35	16.08	14.08

Table 7.2. Compaction test data: Modified Proctor (TRINDADE et al., 2006a)

Amount of RBI Grade 81 (%)	Soil 1		Soil 2		Soil 3	
	γ_{dmax} (kN/m ³)	w_{opt} (%)	γ_{dmax} (kN/m ³)	w_{opt} (%)	γ_{dmax} (kN/m ³)	w_{opt} (%)
0	15.17	27.32	17.49	14.31	19.68	9.95
6	14.35	30.35	16.92	16.11	18.12	12.10

Microanalysis was performed in the samples used in the physicochemical analysis reported in item 7.2.2.2 of this paper. The samples of soils 1, 2 and 3 and their mixtures with 6% of stabilizer were fixed on aluminum stubs using double faced carbon adhesive tape. Next, a coating of carbon conductor film was applied using a Balt-Tec MED 020 metalizer. After sample preparation, photographs were taken using a SEM model JEOL JSM 6360-LV attached to a backscattering detector and energy dispersive X-ray spectrometer (EDS) with Si(Li) 10 mm² detector, 136 eV energy resolution, manufactured by Thermo Electron Company. The analyses were performed at the Campinas State University (UNICAMP) Chemistry Institute, located in the city of Campinas, São Paulo state, Brazil. In the samples of soil 1 and its mixture prepared with 6% of stabilizer were also performed microchemicals mapping from a 55 mm distance (surface-detector) at voltage of 20 kV and 5 A. After testing each sample the EDS was recalibrated using a copper standard. Microchemicals maps of selected particles were obtained considering the most important chemical elements present in the tested samples (Si, Al, Fe, S and Ca). EDS qualitative spectrums obtained from the analyses were recorded in a computer hard disk for quantitative determination of chemical composition of each tested sample using a Noran System SIX Corporation dedicated software that quantifies the percentages of each chemical element ($Z > 11$) based on the hypothesis that they are in the oxide form. The results of the analysis were based in the average of 10 to 20 isolated determinations, as depicted in Figure 7.1.

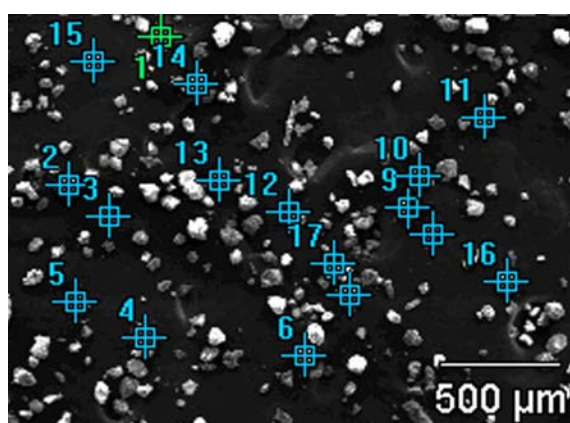


Figure 7.1. Selected particles to perform microanalysis and quantify chemical elements presents in a soil sample.

7.3. Results and evaluation

7.3.1. Physical and chemical properties of the soils and mixtures

The physical and chemical characteristics of civil engineering construction materials must be known to classify them for their potential uses. To meet this requirement, physical and chemical characterization experiments were carried out on the materials under study.

The results of the sieve and sedimentation analysis are presented in Figure 7.2. This figure shows the grain size distribution curves of the soils and their respective mixtures with the chemical additive studied and the quantities of the clay ($\phi \leq 0.002$ mm), silt ($0.002 < \phi \leq 0.06$ mm) and sand ($0.06 < \phi \leq 2$ mm) fractions defined by the grain size distribution scale proposed by the ABNT (1995).

Comparison of the grain size distribution curves in Figure 7.2 shows that the chemical additive altered the original particle distribution of all soils. It is believed that the small particles in the soils agglutinated, forming larger sized flakes, as observed especially in soil 1 (Figure 7.2a) where, with the increase in the amount of additive, the percentage of the clay fraction decreased significantly and the silt and sand fractions increased. A small variation was observed in this performance in soils 2 and 3 (Figures 7.2b and 7.2c, respectively), because with the increase in the additive content the percentage of the clay and silt fractions decreased but the sand fraction increased. When 6% chemical additive was added to the soils, the percentages of particles smaller than 0.002 mm decreased from 61%, 15% and 13% to 29%, 13% and 6%, respectively, in soils 1, 2 and 3, proving that the predominant reactions were those of flocculation, characteristic in clay surfaces with a high concentration of Ca^{2+} ions. This conclusion was reinforced by the observation that the modifications produced by the additive in the granular soils were more significant in soil 1, which consisted of 61% clay particles (particle diameter less than 0.002 mm).

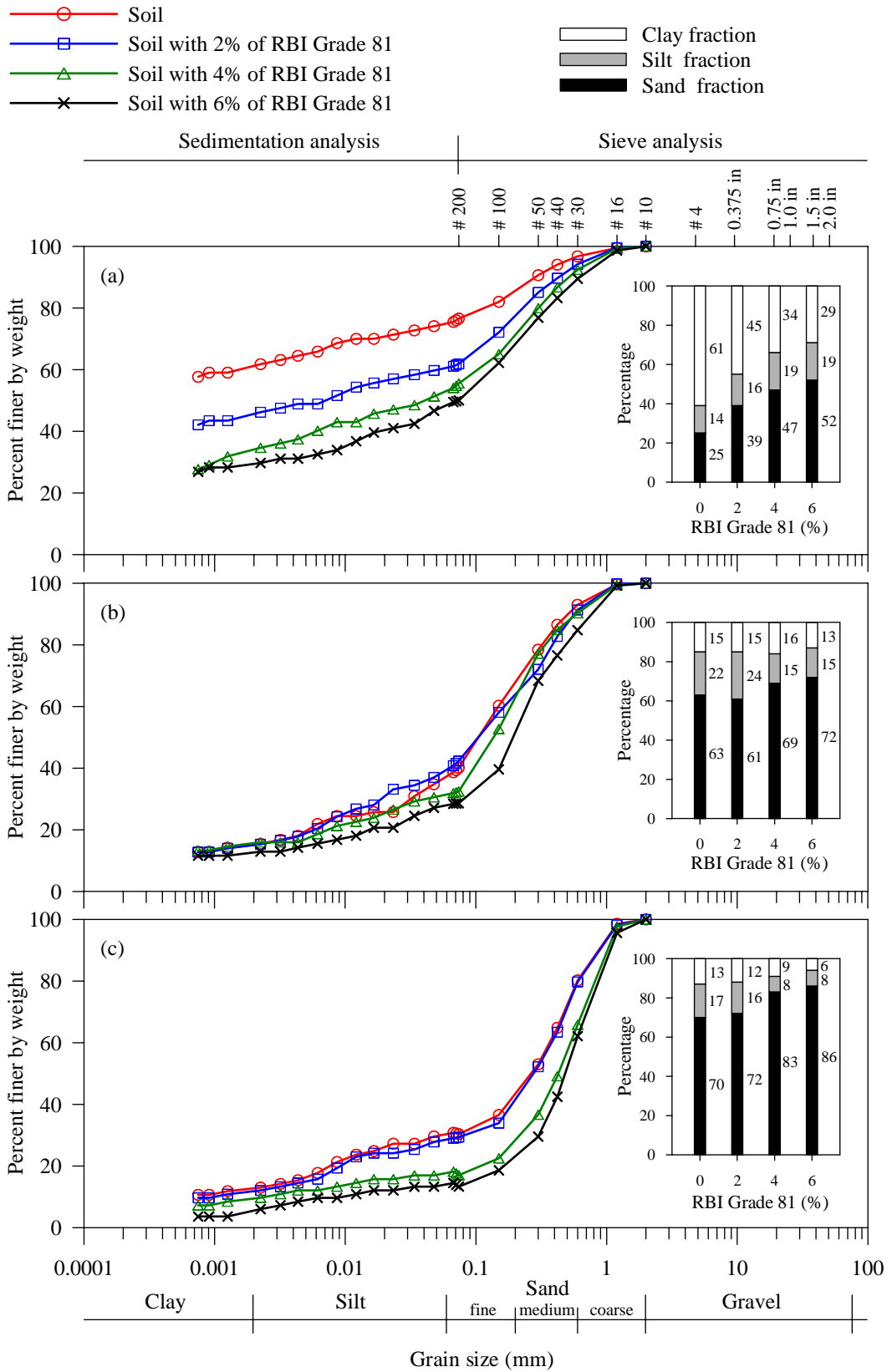


Figure 7.2. Grain size distribution curves and percentages of clay, silt and sand fractions in soils and soil-mixtures: (a) soil 1; (b) soil 2; and (c) soil 3.

The occurrence of significant grain size modifications in soils has been reported in the literature by Guimarães (1971), who detected significant changes in clay soils after adding lime at 3% and 5%, Osula (1996), who added 1%, 2% and 3% Portland cement and hydrated lime to a laterite, and Cristelo and Jalali (2004), who added 2% hydrated lime to two residual granite soils.

In a recent paper on the determination of shear strength and elastic properties of soils-RBI Grade 81 mixtures via triaxial tests, Trindade et al. (2006b, 2006c) reported gains in the peak friction angle of specimens cured for seven days in a wet chamber and associated them to changes in grain size distributions due to flocculation/agglomeration and consequent increase in soils grain size. This assumption is confirmed by data presented in Figure 7.2.

Tables 7.3 to 7.5 show the effects of increasing additive content on the grain unit weight (γ_s) of soils and mixtures. The addition of the stabilizer produced small alterations in the values of this parameter, as expected, because the product has γ_s approximately equal 25 kN/m^3 (ANYWAY, 2004), that is, a value close to those reported for soils without treatment.

Regarding the consistency indices of the soils and mixtures, the data presented in Tables 7.3 to 7.5 show that generally there were slight increases in the plasticity limit values (PL) but reductions in the liquidity limit values (LL) and the plasticity Index (PI) of the soil with the increase in the quantity of chemical additive. The only combination that showed a reduction in PL compared to the natural soil was the mixture of soil 1 with 6% additive.

The changes in plasticity presented in Tables 7.3 to 7.5 suggest that there may have occurred not only cationic exchanges but also alterations in the structure of the fine soil particles via their flocculation and cementation. These results may reflect directly on the performance of these materials in the field, affecting aspects and parameters such as workability, swelling and compaction moisture. Similar conclusions are reported by Guimarães (1971), Transportation Research Board (TRB, 1976), Osula (1996), Çokça (2001) and Cristelo and Jalali (2004) where hydrated lime, Portland cement and fly ash were used as stabilizing agents.

Table 7.3. Physical and chemical properties of soil 1 and its mixtures

Soils characteristics			Amount of RBI Grade 81 (%)			
			0	2	4	6
Physical	γ_s	kN/m ³	27.05	27.05	27.02	26.77
	LL	%	74	61	56	52
	PL	%	33	42	39	36
	PI	%	39	19	17	16
Chemical	pH H ₂ O (1:2,5)	-	6.1	8.2	9.1	9.7
	K ⁺	cmol _c /kg	0.05	0.13	0.25	0.41
	Na ⁺	cmol _c /kg	0.02	0.03	0.05	0.06
	Ca ²⁺	cmol _c /kg	0.94	17.27	25.31	39.07
	Mg ²⁺	cmol _c /kg	0.09	0.12	0.29	0.31
	Al ³⁺	cmol _c /kg	0.00	0.00	0.00	0.00
	H ⁺ + Al ³⁺	cmol _c /kg	0.99	0.00	0.00	0.00
	SB	cmol _c /kg	1.10	17.56	25.91	39.85
	CEC	cmol _c /kg	2.09	17.56	25.91	39.85
	V%	%	52.6	100.0	100.0	100.0

Table 7.4. Physical and chemical properties of soil 2 and its mixtures

Soils characteristics			Amount of RBI Grade 81 (%)			
			0	2	4	6
Physical	γ_s	kN/m ³	25.44	25.92	25.33	25.79
	LL	%	38	37	36	35
	PL	%	25	25	27	29
	PI	%	13	12	9	6
Chemical	pH H ₂ O (1:2,5)	-	5.4	8.5	9.6	9.8
	K ⁺	cmol _c /kg	0.01	0.12	0.18	0.21
	Na ⁺	cmol _c /kg	0.01	0.03	0.06	0.08
	Ca ²⁺	cmol _c /kg	0.42	15.59	24.67	35.44
	Mg ²⁺	cmol _c /kg	0.04	0.15	0.08	0.07
	Al ³⁺	cmol _c /kg	0.32	0.00	0.00	0.00
	H ⁺ + Al ³⁺	cmol _c /kg	1.32	0.00	0.00	0.00
	SB	cmol _c /kg	0.49	15.88	24.99	35.80
	CEC	cmol _c /kg	1.81	15.88	24.99	35.80
	V%	%	27.1	100.0	100.0	100.0

Table 7.5. Physical and chemical properties of soil 3 and its mixtures

Soils characteristics			Amount of RBI Grade 81 (%)			
			0	2	4	6
Physical	γ_s	kN/m ³	25.24	25.71	25.79	25.62
	LL	%	29	27	26	25
	PL	%	20	20	22	22
	PI	%	9	7	4	3
Chemical	pH H ₂ O (1:2,5)	-	5.3	8.5	9.8	10.0
	K ⁺	cmol _c /kg	0.18	0.26	0.30	0.32
	Na ⁺	cmol _c /kg	0.02	0.08	0.10	0.11
	Ca ²⁺	cmol _c /kg	0.59	13.83	23.66	35.98
	Mg ²⁺	cmol _c /kg	0.25	0.09	0.05	0.04
	Al ³⁺	cmol _c /kg	1.02	0.00	0.00	0.00
	H ⁺ + Al ³⁺	cmol _c /kg	1.54	0.00	0.00	0.00
	SB	cmol _c /kg	1.04	14.25	24.11	36.46
	CEC	cmol _c /kg	2.58	14.25	24.11	36.46
	V%	%	40.3	100.0	100.0	100.0

An interesting characteristic of the RBI Grade 81 is that it is recommended to stabilize a wide range of soils, ranging from sand to plastic clay (ANYWAY, 2001). Thus, in a first analysis, it can be inferred that this stabilizer has elements in common with Portland cement and lime in its chemical composition. Hilt and Davidson (1960) analyzed the mechanical performance of clay soil and lime mixtures and considered the possibility of the existence of a limit condition at which, primarily, the stabilizer should meet the affinity of these soils to lime, defining it as its lime fixation capacities. In this study, these authors concluded that: (i) the addition of small quantities of lime to clay soils led to significant increases in net PL, and these were more expressive in soils rich in montmorillonite than those rich in kaolinite; (ii) the addition of amounts of lime lower than the soil fixation point can lead to significant changes in its workability, but not in its mechanical strength.

Thus, when small quantities of lime are added to clay soils, significant variations occur in their PL, but inexpressive changes in the mechanical strength, because there is no lime available for significant pozzolanic reactions to take place; for larger quantities of additive, the PL tends to remain unaltered, verifying the availability of lime for pozzolanic reactions to take place that can lead, if they are reactive to lime, to significant variations in their mechanical strength. Thus the PL parameter can be considered a good indication of the lime fixation point of a soil. Similarly, Marks III

and Haliburton (1970) widened this discussion, understanding that the lime fixation point of a clay soil corresponds to the maximum compression condition of the diffuse double layer of its clay particles, and there is no later reduction in its plasticity, because the superficial charges of these particles reached a condition of equilibrium. Thus in this type of soil, there is a limit for plasticity reduction. In the present study, it was observed that modifications took place in the soil consistency indices with the addition of the stabilizer, and small falls in LL and slight increases in PL were observed, except in soil 1, and a gradual fall in PI, that was more pronounced in soil 1 stabilized with 2% additive. When the concept of the lime fixation point was applied to the data in the present study, it was associated with the 2%, 6% and 4% contents, respectively to soils 1, 2 and 3, as shown in Figure 7.3. However, this type of performance was not observed clearly and easily in the mixtures analyzed here.

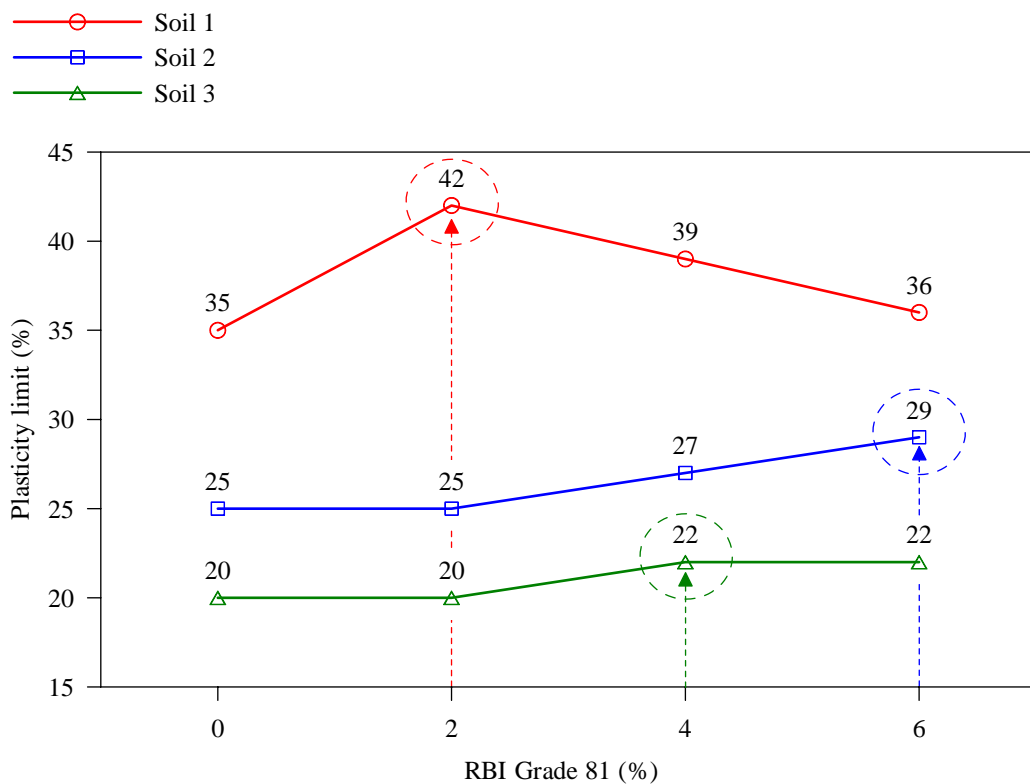


Figure 7.3. Minimum RBI Grade 81 content (% by dry weight) regarding the application of the lime fixation concept to soils 1, 2 and 3.

The soil chemical characterization experiments have frequently been carried out in studies in the soil science field for fertilizer and nutrient replacement practices for

plant growth. Soils, for example, with high cationic exchange capacity are considered as being fertile. In the geotechnical area, these experiments have been carried out to assess, for example, the degree of soil weathering, soil potential for liner applications in environmental geotechnical engineering and the soil reaction potential to chemical stabilizers.

Tables 7.3 to 7.5 show the results of the chemical characterization of the soils and soil-mixtures. The pH values, measured in water following the 1:2.5 volumetric soil:solution ratio of soils 1, 2 and 3 were, respectively, 6.1, 5.4 and 5.3, characterizing soil 1 as slightly acid and soils 2 and 3 as acid according to terminology by Guimarães (2002). According to van Raij et al. (1987) soil pH values are generally between 4 and 7, and values below this range indicate the presence of free acids and values above this value indicate the presence of saline or limestone soils. The cationic exchange capacity (CEC) values in soils 1, 2 and 3 were relatively low and compatible with the mineralogy of their clay fractions, which were predominantly composed of kaolinite and iron and aluminum oxides, which are secondary minerals that have, respectively, CEC in the range from 3 to 15 cmol_c/kg (GUIMARÃES, 1971) and 2 to 4 cmol_c/kg (MEURER et al., 2004). Regarding the percentage base saturation (V%), soils 1, 2 and 3 presented values lower than 60%. According to Brady and Weil (1999), soils from tropical and wet regions, in which silicate clays predominate, are acid when V% is lower than 80%. Therefore the V% values are in line with the pH values determined and with the clay minerals present in the soils studied. The potential acidity ($\text{H}^+ + \text{Al}^{3+}$) values of soils 1, 2 and 3 were, respectively, 0.99, 1.32 and 1.54, that is, they presented an inverse relationship with the pH values, showing that the potential acidity and consequently, some of the hydrogen and aluminum compounds influenced the pH means of the soils. Brady and Weil (1999) commented that the factors that account for soil acidity are complex, because there are two groups of dominant elements that exercise influence in the soil at the same time: acidity derives from aluminum and hydrogen while most of the other cations neutralize it.

Tables 7.3 to 7.5 show that when the chemical additive was added to the soils there were significant increases in the value of the following chemical characteristics: pH, sum of exchangeable bases (SB) (mainly due to the increase in the Ca^{2+} ions), CEC and V%. In contrast, there was an expressive reduction in the quantity of free hydrogen and aluminum and the quantitative sums of $\text{H}^+ + \text{Al}^{3+}$ became nil after stabilizing the

soils with the additive under study. In short, the incorporation of the chemical stabilizer in the soils accounted for the increase in saturation of bases and for the total consumption of the exchangeable $H^+ + Al^{3+}$ ions, generating sharp modifications in the pH from acid to alkaline.

Among the chemical characteristics assessed in the present study, the pH has been the most used in studies of soil chemical stabilization. It is known that increased pH causes the partial dissolution of mineral constituents of the soils generally followed by the formation of new silicates and aluminates, stable in the new conditions, which associate, forming a cement-like product capable of conferring high mechanical strength to the material (CHAUVEL and NÓBREGA, 1980). For instance, some studies sought to establish dosing criteria based on the pH values of the stabilized material, such as the classic study by Eades and Grim (1966) and recently the standard test method presented by American Society for Testing and Materials (ASTM, 1999). In these publications it is proposed a method to determine the ideal quantity of lime to stabilize a soil determining its lime reactivity level, which consisted of measuring the pH of the mixture after one hour. This value was then related to the quantity of lime consumed in the reactions in this time interval relating the optimum lime content to the smallest quantity of lime that raises the pH of the mixtures to 12.4. However, it is believed that dosage criteria based on the pH value that causes attack on the silica and aluminum present in the soil should be studied in depth, especially in the case of chemically stabilized tropical soils. Some studies carried out in tropical soils have reported that the addition of quantities from 2% to 5% Portland cement (PESSOA, 2004) and hydrated lime (LIMA, 1981; CARVALHO et al., 1981; PESSOA, 2004) was responsible for sharp increases in the pH, and values greater than 12.0 were observed. On the other hand, Rezende (2003) studied clay soils from the subgrade of two Brazilian highway experimental roads constructed in Brasilia-DF and did not observe pH values greater than 10.9 even after adding up to 6% hydrated lime.

In the present study, it was verified that when 2% to 4% chemical additive was added to soils the pH value increased significantly, but more variations were observed at 4% and 6% quantities and there was a slight tendency to stabilization in the pH values around 10.0, as shown in Figure 7.4.

Based on the chemical equilibriums reported by Lindsay (1976), curves were constructed that represented the conditions which under silica and aluminum

solubilization in water takes place, in function of the pH values. Figure 7.4 shows that in the soils the aluminum was practically insoluble and the silica presented solubility between 25 and 30 cmol/L, but with the addition of 6% chemical additive the solubilities of silica and aluminum raised to, respectively, 65 and 50 cmol/L in soils 1 and 2. In the case of soil 3, when the pH reached 10.0, silica presented solubility about 75 cmol/L and aluminum was totally soluble.

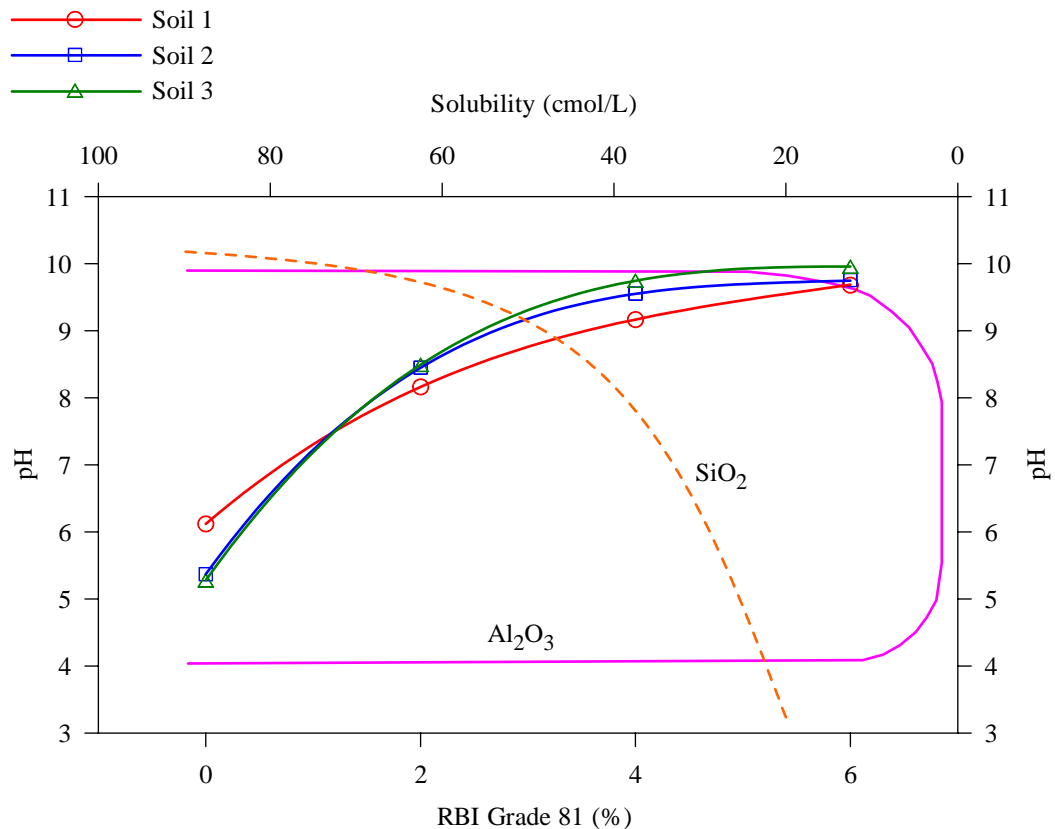


Figure 7.4. pH of soils 1, 2 e 3 and its mixtures and basic curves of silica (SiO₂) and alumina (Al₂O₃) solubilization.

7.3.2. Mineralogical characterization of soils and mixtures

Most of chemical reactions between soil and chemical stabilizer are soil minerals dependent, and identification of mineral type in the soil different fractions is mandatory to soil stabilization studies to understand the process as a whole. Therefore, the kinds of minerals present after the soil stabilization can become a good tool for diagnosis on the soil behavior, which could complement the studies involving the physical and chemical characteristics of the final product after stabilization.

Figures 7.5 and 7.6 show data from XRD (X-ray diffraction) analyses performed on soil samples 1, 2 and 3 and their 7-days curing mixtures with 2%, 4% and 6% RBI Grade 81 contents. Samples were prepared using soils sand ($\geq 53 \mu\text{m}$) and silt-clay ($< 53 \mu\text{m}$) fractions. Tables 7.6 and 7.7 show values of peak intensity of the minerals identified in each of the tested soils and mixtures.

Sand fractions for soil samples 1, 2 e 3 and their admixtures are very similar and present, essentially, quartz that was identified by peaks corresponding to d's (atomic interplanar distance) 0.43, 0.33, 0.25 and 0.23 nm (GRIM, 1968; MOORE and REYNOLDS JR., 1989). In the sand fraction of soil 3 and its mixtures it was identified K-feldspars due to peaks obtained at 0.32 nm (GRIM, 1968; MOORE and REYNOLDS JR., 1989). Additionally to quartz and feldspar, also were detected peaks that allowed to identify kaolinite (0.72 and 0.36 nm) in the sand fractions of soils 2 and 3 and their admixtures. The presence of kaolinite in these samples can be associated to the pseudomorphs inherited from the weathering of feldspar or muscovite that are commonly found in these soils, as related by Pinto et al. (1972). The Figure 7.7 presents an example of the kaolinite in mica pseudomorphics forms found in soils 2 and 3. From the data presented in Figure 7.5 and Table 7.6, it can be seen that there was a progressive decrease in the intensity of the peaks from quartz and feldspars detected in $\geq 53 \mu\text{m}$ fraction at the same time that there was an increase in the chemical stabilizer content, showing that stabilization process was destroying part of these minerals through of the short- and medium-term chemical reactions that have been developed.

The XRD patterns presented in Figure 7.6 show the silt-clay fraction of all soil samples and their mixtures. They show that kaolinite, quartz and goethite, identified by their peaks of d's equal to 0.72, 0.33 and 0.42 nm, respectively, appeared in all $< 0.53 \mu\text{m}$ fractions of soil samples and its mixtures. In samples from soils 1 and 2 and its mixtures was detected gibbsite ($d = 0.49 \text{ nm}$). From peaks at positions corresponding to $d = 1.00 \text{ nm}$ and $d = 0.50 \text{ nm}$ it was possible to determine the presence of mica in soil samples 2 and 3 and their mixtures.

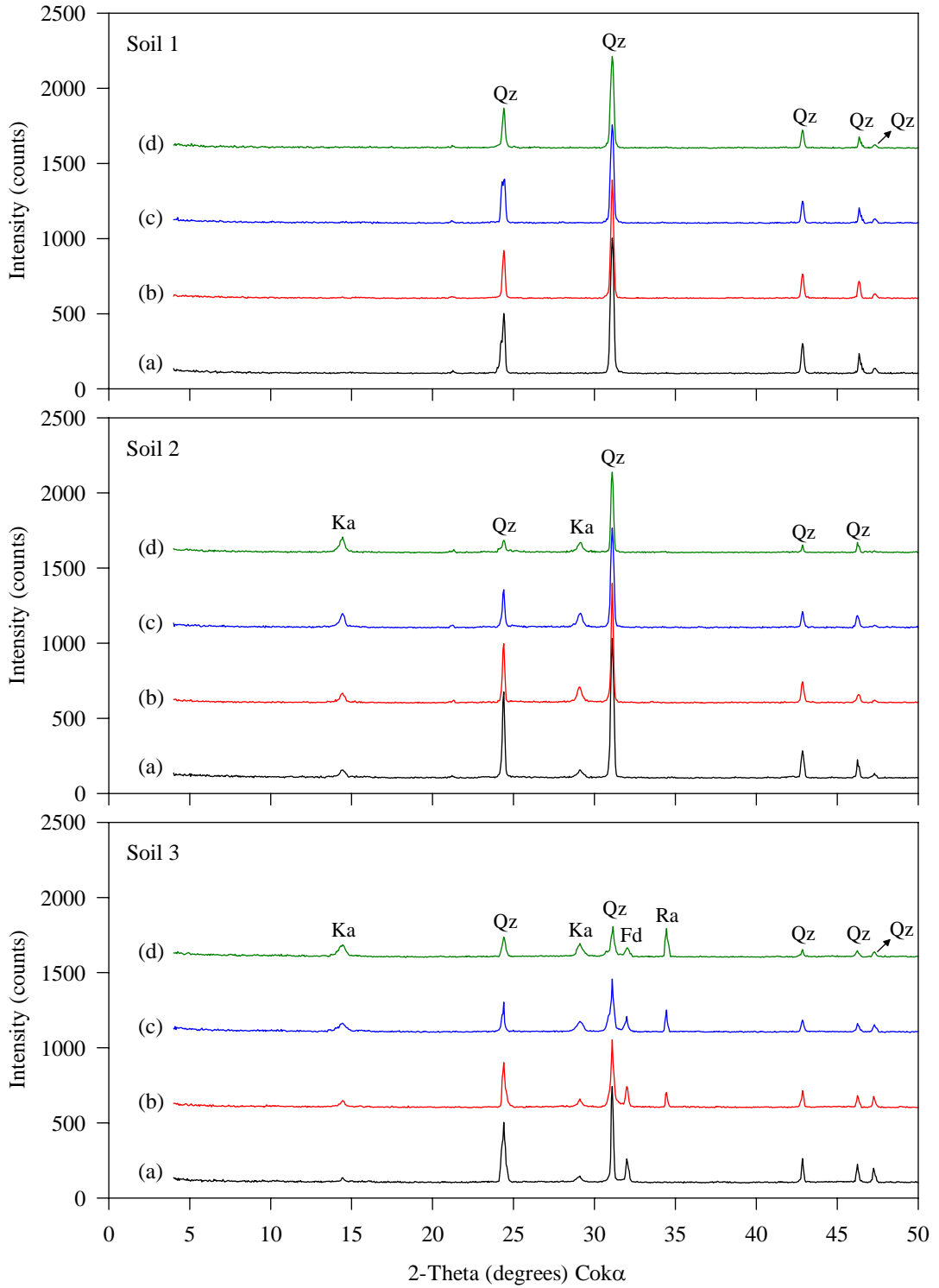


Figure 7.5. XRD patterns of $\geq 53 \mu\text{m}$ fraction of soils 1, 2 and 3 no treated (a) and treated with 2% (b), 4% (c) e 6% (d) of chemical stabilizer. Fd = feldspar (orthoclase) $[\text{K}(\text{Al}, \text{Fe})\text{Si}_2\text{O}_8]$, Ka = kaolinite $[\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4]$, Qz = quartz $[\text{SiO}_2]$ and Ra = rankinite $[\text{Ca}_3\text{Si}_2\text{O}_7]$.

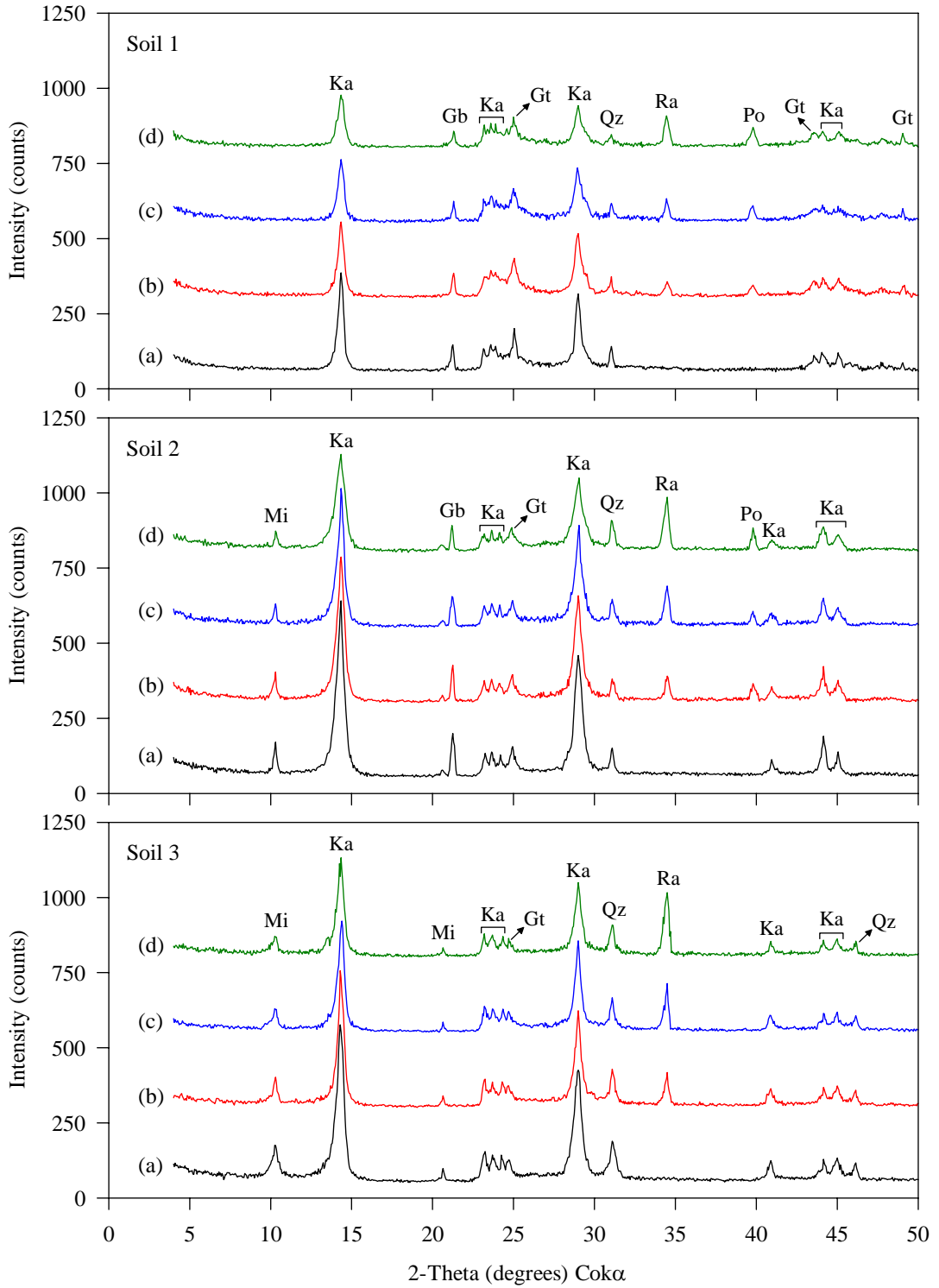


Figure 7.6. XRD patterns of $< 53 \mu\text{m}$ fraction of soils 1, 2 e 3 no treated (a) and treated with 2% (b), 4% (c) and 6% (d) of chemical stabilizer. Gb = gibbsite $[\text{Al}(\text{OH})_3]$, Gt = goethite $[\alpha\text{-FeO}(\text{OH})]$, Ka = kaolinite $[\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4]$, Mi = mica $[(\text{k}, \text{Na})\text{Al}_2(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2]$, Po = portlandite $[\text{Ca}(\text{OH})_2]$, Qz = quartz $[\text{SiO}_2]$ and Ra = rankinite $[\text{Ca}_3\text{Si}_2\text{O}_7]$.

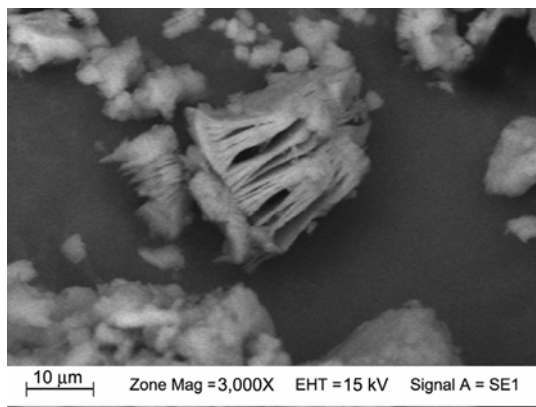


Figure 7.7. Image obtained by secondary electrons signs produced in SEM of one kaolinite in mica pseudomorphs forms flake present in soil 3 sample.

From the analyses of the XRD patterns presented in Figures 7.5 and 7.6, it can be observed that when the chemical stabilizer was added new minerals phases were formed and they were identified. In the silt-clay fraction of mixtures from soil samples 1 and 2 it was noticed the presence of portlandite which is a calcium hydroxide ($d = 0.26$ nm). Rankinite, calcium silicate, was identified by its peaks positions corresponding to a $d = 0.30$ nm (EADES and GRIM, 1960; EADES et al., 1962) and it was found in most of the mixtures, exception in the ≥ 53 μm fraction of mixtures from soil samples 1 and 2 (Figure 7.5). Intense and well defined peaks showed that the mixtures, after seven days cure time, showed the formation of a significant amount of calcium silicate, mainly in the finer fractions. It was also observed that with the increasing of chemical additive contents, the peaks for rankinite also increased indicating a larger formation of cementing compounds associated to the 6% content of RBI Grade 81.

The rankinite, calcium silicate, is a typical product of hydration reactions of the tricalcium silicate (C_3S or 3CaOSiO_2) portland cement (NOBLE, 1967; PETRUCCI, 1998) and from pozzolanic reactions between silica (SiO_2) and calcium oxide (CaO) in soil-lime mixtures (EADES and GRIM, 1960; EADES et al., 1962; SRINIVASAN, 1967; GUIMARÃES, 1971; TRB, 1976; CHAUVEL and NÓBREGA, 1980; LIMA, 1981; CARVALHO et al., 1981). The portlandite [$\text{Ca}(\text{OH})_2$] is a mineral phase present in the RBI Grade 81 (Figure 7.8), which indicates that in soil samples 1 and 2 the reactions between this mineral and the soil minerals didn't occur completely, being necessary a long-term to produce all the reactions. These observations are corroborated

by the data presented by Trindade et al. (2006a, 2006b, 2006c), who, when studying the effect of the RBI Grade 81 addition in the mechanical properties of soils 1, 2 and 3, verified that the higher increases in CBR, unconfined compressive strength, tensile strength and shear strength were associated to soil 3.

Table 7.6. Minerals peak intensities identified in the $\geq 53 \mu\text{m}$ fraction of soils 1, 2 e 3 and its mixtures

Soils samples	Amount of RBI Grade 81 (%)	Minerals peaks intensities associated with its strong lines (d in nm)			
		Fd (0.324)	Ka (0.718)	Qz (0.334)	Ra (0.302)
Soil 1	0	-	-	903	-
	2	-	-	789	-
	4	-	-	656	-
	6	-	-	612	-
Soil 2	0	-	57	932	-
	2	-	68	798	-
	4	-	97	667	-
	6	-	106	538	-
Soil 3	0	160	36	644	-
	2	131	49	454	102
	4	108	64	357	151
	6	65	71	206	194

Table 7.7. Minerals peak intensities identified in the $< 53 \mu\text{m}$ fraction of soils 1, 2 e 3 and its mixtures

Soils samples	Amount of RBI Grade 81 (%)	Minerals peaks intensities associated with its strong lines (d in nm)						
		Gb (0.485)	Gt (0.418)	Ka (0.718)	Mi (0.997)	Po (0.263)	Qz (0.334)	Ra (0.302)
Soil 1	0	97	151	336	-	-	91	-
	2	85	135	255	-	45	73	57
	4	75	117	214	-	60	67	83
	6	58	105	178	-	71	46	109
Soil 2	0	150	106	586	121	-	101	-
	2	127	96	487	104	65	91	90
	4	106	92	415	81	56	96	141
	6	92	84	329	73	84	104	186
Soil 3	0	-	77	526	125	-	139	-
	2	-	68	457	102	-	128	118
	4	-	60	365	77	-	116	164
	6	-	54	333	71	-	109	217

Similarity to the observed in the soils sand fractions, from the data presented in Figure 7.6 and Table 7.7, it was observed that there was a progressive decrease in peak

intensities of all mineral phases originally presents (kaolinite, gibbsite, goethite, quartz and mica) in the silt-clay fraction of soils 1, 2 and 3, with increasing of chemical stabilizer contents. This reinforces the idea that the chemical stabilization process was responsible by consumption part of soil minerals through of the chemical reactions with RBI Grade 81. This hypothesis also presented by Eades et al. (1962), in soil-lime stabilization case, and Noble (1967), in a soil-cement stabilization study, which associated the decreasing in peak intensities of soil minerals to consumption of these minerals, principally the aluminosilicates, though of reactions with constituents of chemical stabilizers studied.

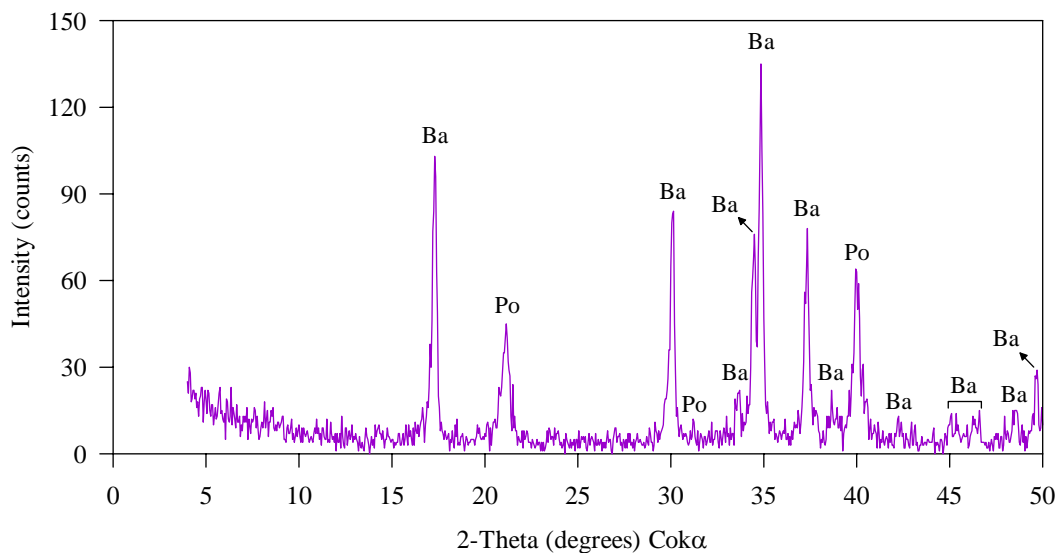


Figure 7.8. XRD pattern of RBI Grade 81 chemical stabilizer. Ba = bassanite $[\text{CaSO}_4(0.5\text{H}_2\text{O})]$, Po = portlandite $[\text{Ca}(\text{OH})_2]$.

7.3.3. Microstructural characterization of soils and mixtures

In stabilization studies of tropical soils, although there are many data of interest on geotechnical properties of these materials, there is very little information at the microscopic level, including aspects such as structural reorganization, compaction and particle cementing, which could offer interesting input for the study of the technical performance of the mixtures. Among the methods available for this purpose, scanning electronic microscopy has been much used to study the microstructure of compacted and chemically stabilized soils, because, according to Pessoa (2004), both compaction

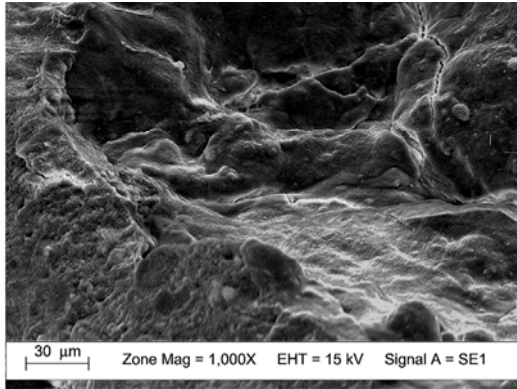
and cationic exchanges and chemical reactions are capable of causing structural rearrangements.

In the scanning electronic microscope (SEM) an electron beam accelerated by an electric field is directed, through a vacuum of 1.33×10^{-6} kPa, to the surface of the sample to be observed. As the result of the interaction of the electrons beam with the sample surface, there is the emission of a series of radiations, including secondary electrons, backscattered electrons, X-rays, Auger electrons, and photons. When correctly captured, these radiations give characteristic data on the sample analyzed, including surface topography, composition and crystallography.

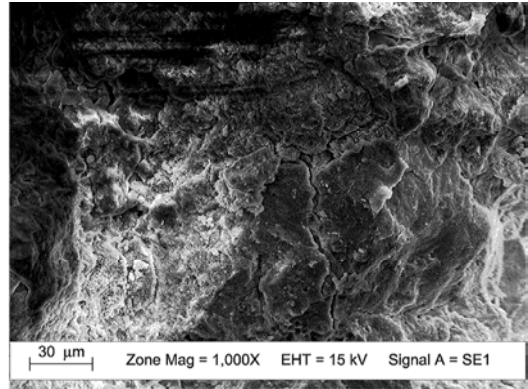
In scanning electronic microscopy, the signals of greatest interest for image formation are the secondary and backscattered electrons. As the primary electron beam scans the sample, these signals are modified according to variations in the surface. The secondary electrons supply images of the sample surface topography and obtain the high-resolution images, while the backscattered electrons give an image characteristic of the variation of the components due to their differences in anatomic densities, where the elements with greater densities present greater brilliance. Depending on the material analyzed, the magnification can reach 900,000 times, but for the analysis of materials commonly used in civil construction, the maximum increase used is 10,000 times.

Initially, the microstructure was characterized from an analysis of the secondary electron images obtained in SEM. Samples from soils 1, 2 and 3 and their mixtures with 6% chemical additive compacted under the optimum conditions (w_{opt} and γ_{dmax}) at the standard and modified Proctor test were analyzed and the images are shown, respectively, in Figures 7.9 and 7.10.

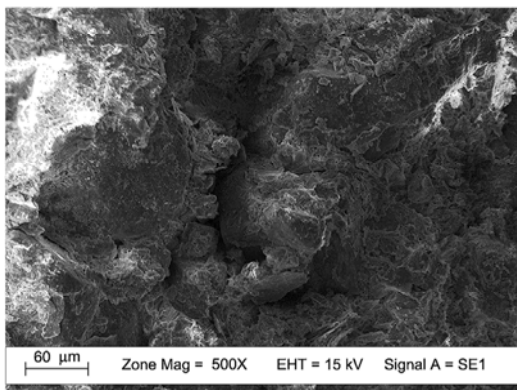
It was observed from the sets of images presented in these figures that the volume of soil 1 was taken up predominantly by plasma that formed a continuous phase and in some cases, was presented in the form of spherical micro-aggregates joined together. These micro-aggregates were formed by a very fine particles, randomly placed, formed by assemblies of kaolinite and gibbsite minerals wrapped and cemented by iron oxyhydroxides responsible for the stability of their organization. On the other hand, it was observed that the predominance of the plasma compared to the skeleton greatly decreased in soils 2 and 3, and in this last material there were 100 to 500 μm quartz grains with little, or practically no, quantity of fine material filling the gaps.



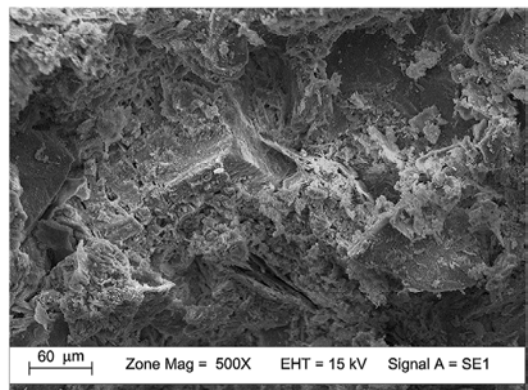
(a)



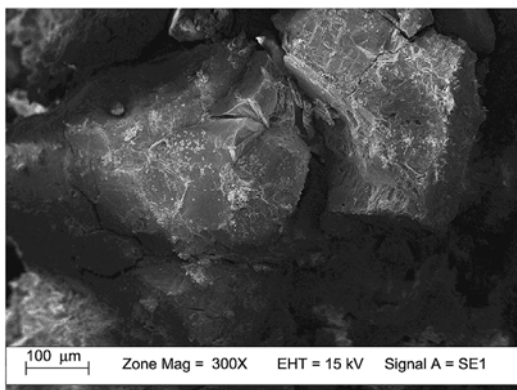
(b)



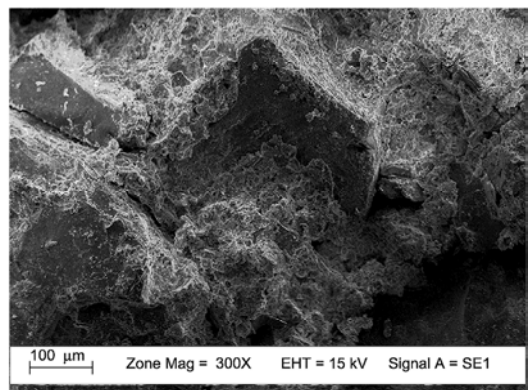
(c)



(d)



(e)



(f)

Figure 7.9. Compacted samples at standard Proctor effort images obtained by secondary electrons signs produced in SEM: (a), (c) and (e), respectively, soils 1, 2 and 3; (b), (d) and (f), respectively, soils 1, 2 and 3 with 6% of chemical stabilizer.

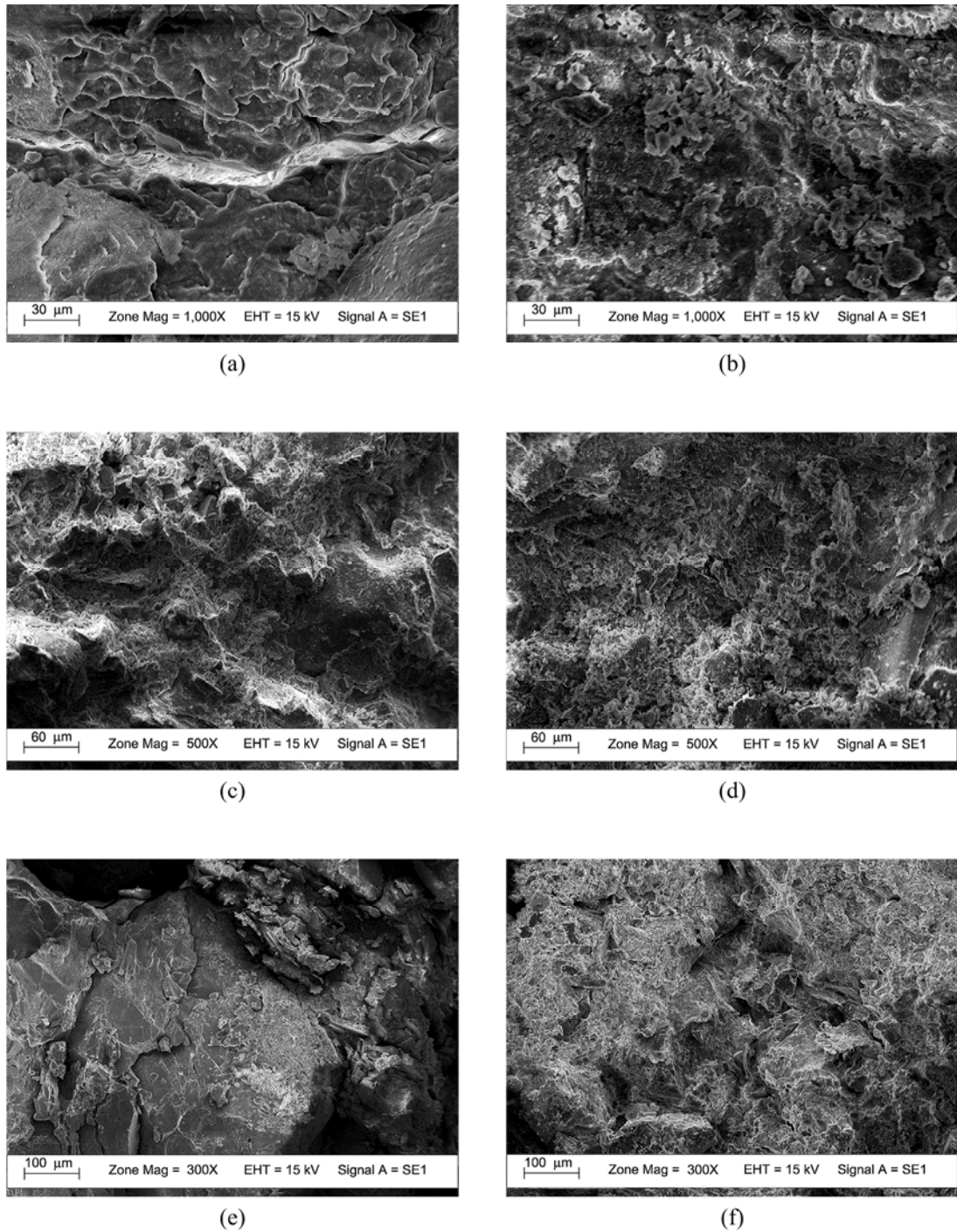


Figure 7.10. Compacted samples at modified Proctor effort images obtained by secondary electrons signs produced in SEM: (a), (c) and (e), respectively, soils 1, 2 and 3; (b), (d) and (f), respectively, soils 1, 2 and 3 with 6% of chemical stabilizer.

The effects of the increase in the compaction effort, from the standard Proctor test to the modified Proctor test, were clearly visible in soils 1, 2 and 3. Figures 7.9 and 7.10 show that the quartz grains, present in large quantities in soils 2 and 3, were broken

after the increase in compaction effort, forming finer and less porous materials. In soil 1, it was observed that after the increase in compaction effort very fine crack gaps arose (0.1 to 10 μm), close to each other and placed perpendicularly to the compaction axle. Figures 7.9a and 7.10a show that these cracks were limited by a paler colored clay film, called stress cutan, according to terminology adopted by Brewer (1976). According to Carvalho et al. (1981), the application of a great compaction effort is not always the best treatment to attain high mechanical strength, and it can lead to the complete destruction of the microstructure of the material, that is sometimes naturally stable, as in the case of the latosols.

Regarding the microstructure of the stabilized soils, Figures 7.9 and 7.10 show that the chemical additive used accounted for the formation of cementation nuclei among the soil micro-aggregates. These nuclei were more obvious in the soil 3 mixtures (Figures 9f and 10f), where there seems to have been SiO_2 and Al_2O_3 solubilization, forming a gel (calcium silicate and/or aluminates) that, after consolidation, cemented the surrounding particles, conglomerating them (EADES and GRIM, 1960; EADES et al., 1962; NOBLE, 1967). In the soil 1 mixtures the addition of the additive conserved the continuous microstructure (Figures 9b and 10b), resulting from the coalescence of the micro-aggregates; however it prevented the formation of plasma orientations and empty cracks, responsible for the lamellation of soil 1 without treatment after applying the high compacting effort, as was the case of the use of the modified Proctor test.

The analysis of the microstructure of the material compacted after adding the chemical additive also explained the results of the grain size distribution analyses presented in item 7.3.1, where the stabilized soils presented a greater quantity of sand compared to the untreated soils. Figures 7.9 and 7.10 show that after soil stabilization the micro-aggregates linked by the cementing nuclei performed as highly stable grains, capable of resisting all the processes used in the grain size distribution test together to disperse the soil particles.

In addition to SEM analysis, the microstructure of soil samples 1, 2 and 3 and of their admixtures with 6% of RBI Grade 81 were described using optical microscopy (OM) performed in specimens compacted at the modified Proctor compaction effort. Optical microscopy is rarely used in soil mechanics studies in Brazil and elsewhere, although it provides one of the simplest and less expensive techniques to study the development of microstructures of soil mixtures, reaching resolutions down to 200 μm .

Figure 7.11a shows that compaction of soil 1 created a clear tendency to packing and virtual coalescence of the ovoidal micro-aggregates, welded face-to-face, turning the soil mass in a higher cohesive structure and forming a typical structure observed in compacted kaolinite latosols (SCHAEFER, 2001). Color was mainly red-dark, different from the yellowish-red color observed in undisturbed soil samples, as reported by Azevedo (1999). The quartz grains in soil 1 were less abundant than the micro-aggregates, with grain size ranging from 0.05 to 2 mm and, usually, with subangular to angular shapes and not oriented. In some cases compaction resulted in a breaking or fracturing of quartz, however most grains were unaffected. Also, the compaction effort created a fissured structure along the lines of particle weaknesses, filled by fine interstitial plasma without apparent orientation.

Similarly to the observed in SEM images, the addition of 6% of chemical stabilizer to soil 1 produced significant reduction of its fissure formation pattern (Figure 7.11b), and all remaining voids were filled by a fine yellowish-red material. This material was probably a mixture of the partially solubilized oxides in high pH resulting from the stabilizer addition.

Soils 2 and 3 present an organization of plasma-skeleton of the granitic type, exhibit small portions with agglomeroplasmatic type, in which no clay aggregates occur (Figures 7.11c and 7.11e). The nodules are common and typically pseudomorphic, showing subrounded smoothed grain, without fracturing and lacking orientation. Structural elements are linked through clay bridges or are embedded in the scarce plasma. In these soils, compaction led to an extreme reduction of structural voids, mainly presenting small channels and chambers and, less commonly, in the form of packing voids. The quartz grains are dominant in soils 2 and 3. In the case of the soil 2, the grains are small, subrounded to subangular, with average size of 0.2 mm (Figure 7.11c). On the other hand, quartz and feldspar grains in soil 3 are considerably larger, with average size of 0.5 mm, with a considerable amount of quartz grains bigger than 1 mm (Figure 7.11e). These showed little fracturing and no evidence of corroded surfaces.

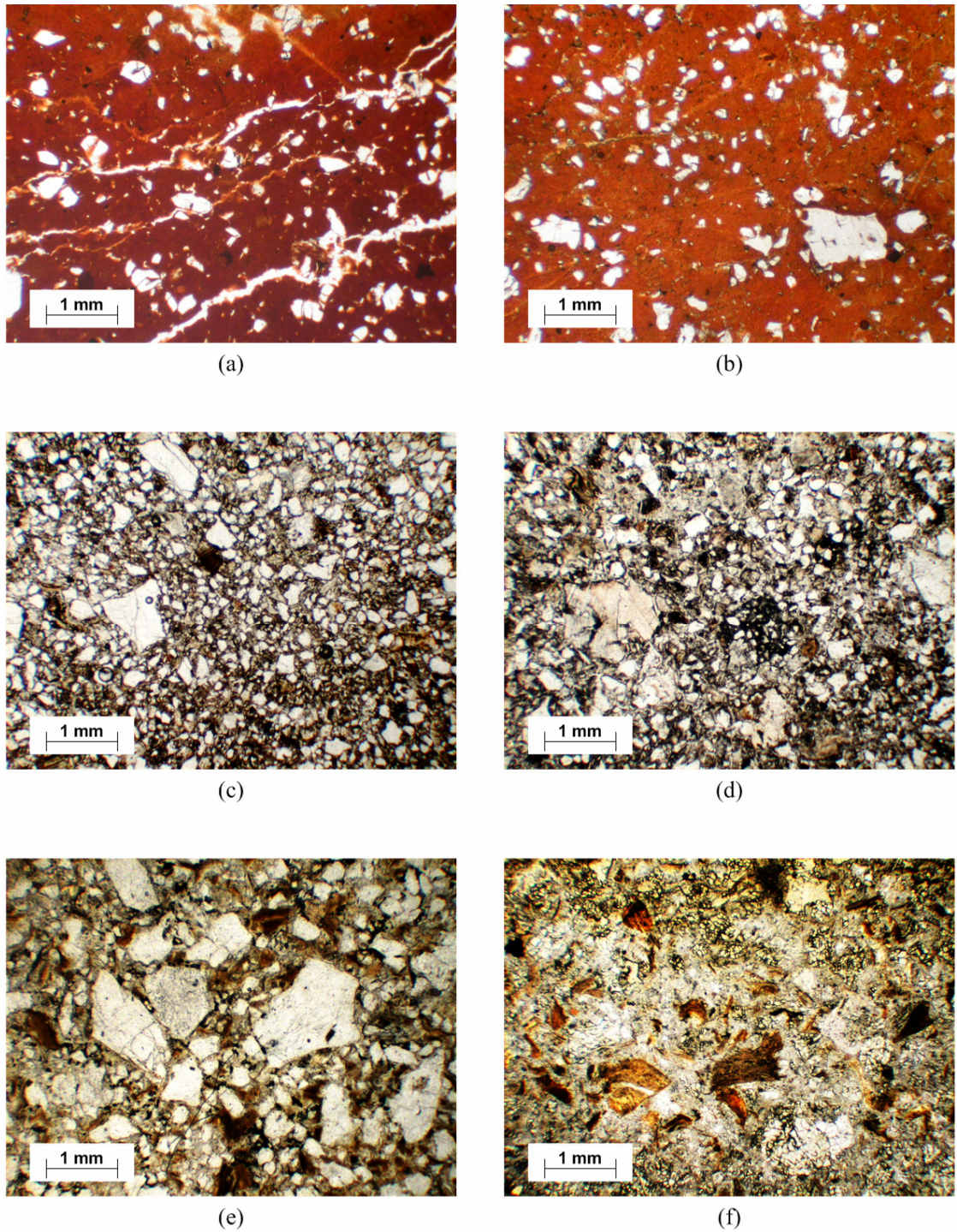


Figure 7.11. Compacted samples at modified Proctor effort images obtained by OM: (a), (c) and (e), respectively, soils 1, 2 and 3; (b), (d) and (f), respectively, soils 1, 2 and 3 with 6% of chemical stabilizer.

Undisturbed samples of soils 2 and 3 present kaolinite pseudomorphs after mica dispersed in the soils masses, as described by Azevedo (1999). According to this

author, compaction effort promoted repacking and reorientation of these pseudomorphs forming horizontal lines parallel to the specimen's surface, and normal to the direction of the applied compaction effort.

Regarding the mixtures of soils 2 and 3 stabilized with 6% of RBI Grade 81, the images presented in Figures 7.11d and 7.11f are consistent with SEM observations. Mainly in soil 3, it was observed that quartz and feldspar grains were mostly destroyed and solubilized, and the few remaining grains became fractured after the soil stabilization process. The solubilized material formed a sort of cementing gel that involved the micro-aggregates, pseudomorphs and remaining grains, forming a structurally dense soil mass, highly resistant.

In the soil 3 mixture it was also possible to identify the formation of a red to yellow cementing material (Figure 7.11f) that is, probably, constituted by the same material that filled out the fine crack gaps of soil 1 after its chemical stabilization. Although not having observed through the analyses of XRD presented in Figures 7.5 and 7.6 the formation of others minerals besides the rankinite ($3\text{CaO}\cdot 2\text{SiO}_2$), it is believed that the yellow to red cementing material is formed starting from the reaction of the calcium hydroxide [$\text{Ca}(\text{OH})_2$] present in RBI Grade 81 (Figure 7.8) together with the iron and aluminum oxides (respectively, Fe_2O_3 and Al_2O_3) present in the soils, creating the $4\text{CaO}\cdot \text{Al}_2\text{O}_3\cdot \text{Fe}_2\text{O}_3$, also known as the C_4F commonly found in the constitution of the Portland cements.

To complement the results of the present study, a specific study was directed to the qualitative and semiquantitative determination of the presence of chemical elements in the soils and in their mixtures using the microanalysis technique.

The microanalysis is one of the most important instruments for the chemical analysis of organic and inorganic materials. Through the identification of the X-ray emitted by the sample, when of the interaction with the electrons beam, it is possible to determine the composition of areas over $1\ \mu\text{m}$ of diameter. It is a non-destructive technique that can determine amounts from 0.1% of present elements in the sample, since $Z > 11$ in the case of EDS (energy dispersive X-ray spectrometer) and $Z > 4$ in the case of WDS (wavelength dispersive X-ray spectrometer). It should be pointed out that in the EDS technique presence of the carbon element can be related to the coating of the carbon conductor film applied over the sample before testing. In the present research it

was used a EDS probe and Figures 7.12 and 7.13 show data of soils 1, 2 and 3 and of theirs mixtures with 6% of RBI Grade 81.

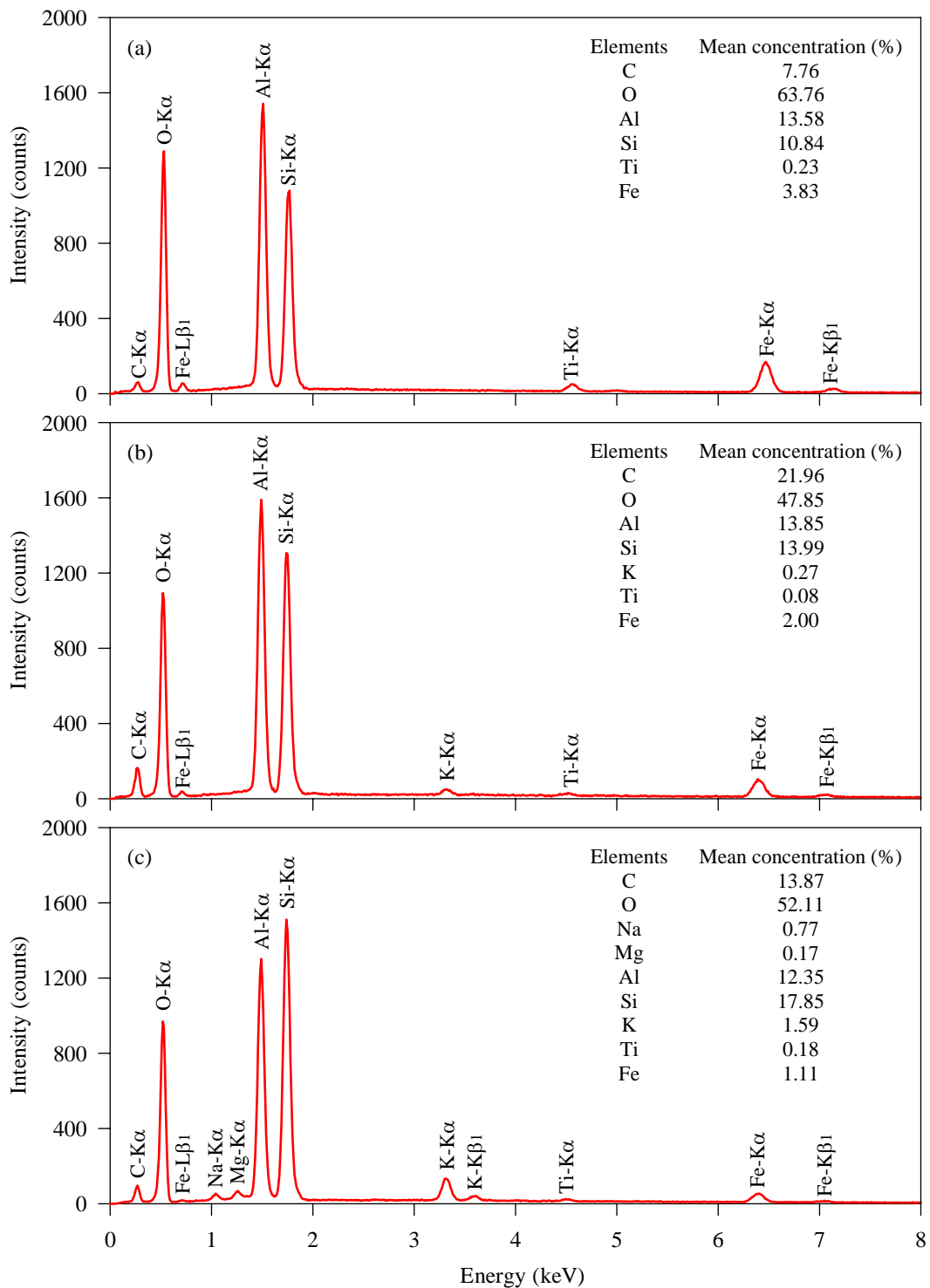


Figure 7.12. EDS spectrum and chemical elements mean concentration determined to: (a) soil 1; (b) soil 2; and (c) soil 3.

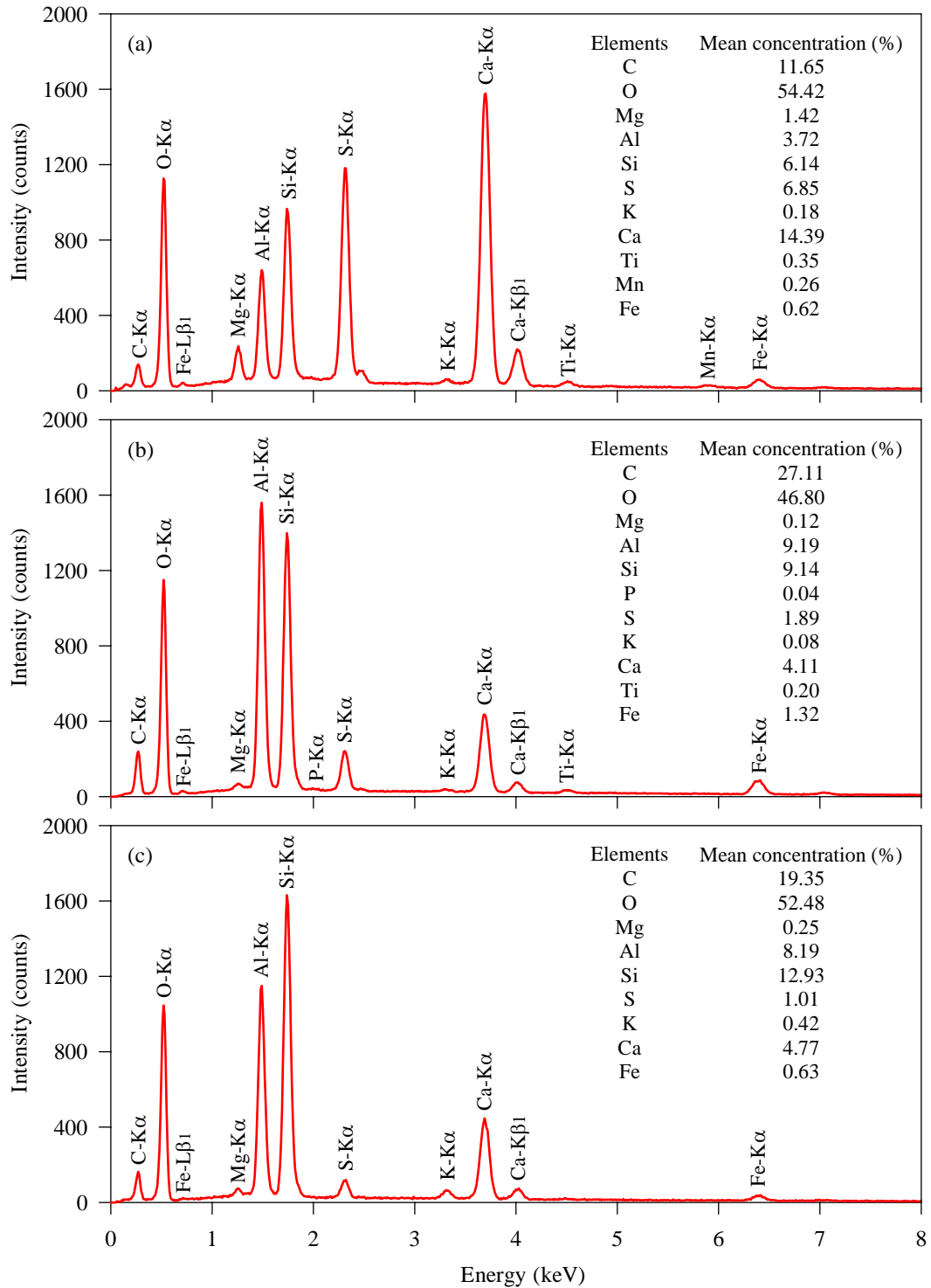


Figure 7.13. EDS spectrum and chemical elements mean concentration determined to: (a) soil 1 with 6% de chemical stabilizer; (b) soil 2 with 6% de chemical stabilizer; and (c) soil 3 with 6% de chemical stabilizer.

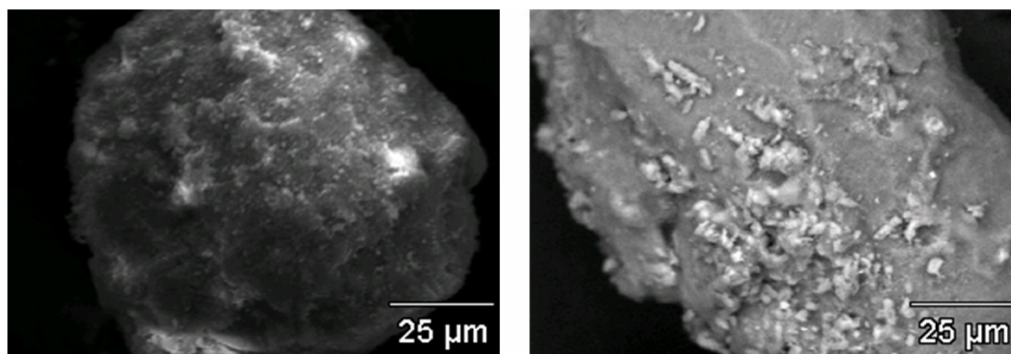
The EDS spectrums presented in Figure 7.12 shows that the soils 1, 2 and 3 are constituted, basically, by Al, Si and Fe. However, other elements were also detected in smaller amounts, as it is the case of Na, Mg, K and Ti. It should be referred that the elements Na and K were just found in the soils 2 and 3 (Figures 7.12b and 7.12c) being associated to the K-feldspar and mica mineral groups as illustrated in Figures 7.5 and 7.6. The largest amount of Fe was determined in soil 1 (Figure 7.12a), a yellowish-red latosol with reasonable goethite presence (Figure 7.6). Great amounts of Al and Si were encountered, probably, associated to the minerals kaolinite and quartz which are the most abundant in the three analyzed soils.

From the ESD spectrums illustrated in Figure 7.13, it was also verified the main elements found in the mixtures of the soils 1, 2 and 3 with 6% of RBI Grade 81 that most important elements present are Al, Si, Ca and S. But Mg, P, K, Mn, Ti and Fe were also detected in smaller amounts.

Also, microchemical analysis were performed to quantify the cementation process created by addition of 6% of stabilizer to the soil 1, furnishing semiquantitative microchemical charts of this soil and its mixture (Figure 7.14).

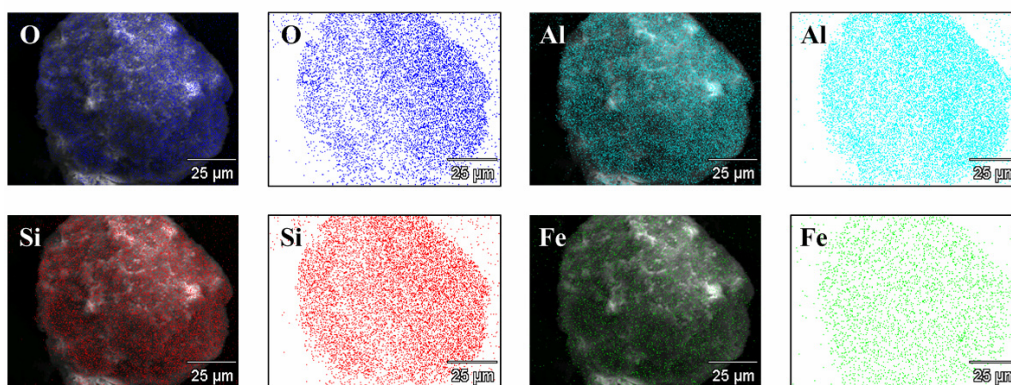
The data presented in Figure 7.14c are in agreement with those from the microanalysis (Figure 7.12a), and show that the soil 1 is constituted basically by Si, Al and Fe oxides. From the data presented in Figure 7.14d it can be observed that in the mixture of the soil 1 with 6% of RBI Grade 81 are detected, also, Ca and S that are concentrated in the areas of assembly of crystals. In these areas, together with the Ca and S, it is verified presence of an expressive amount of O, Al and Si.

The micro-aggregates in the form of small sticks presented in Figure 7.14b and 7.14d, probably, are constituted by bassanite or gypsum [$\text{CaSO}_4(0.5\text{H}_2\text{O})$], which is also a material present in the RBI Grade 81 (Figure 7.8). Other minerals that, probably, were formed in the stabilization process of soil 1 were the calcium, aluminum and iron silicates and the sulfoaluminate, that is a solid element that lodges in the pores of the soil mass turning them more compact, since there is not excess of calcium oxide dissolved in the interstitial water that, in contact with the sulfoaluminate, can create the ettringite (hydrated calcium aluminum sulfate hydroxide), which is an extremely expansible and very common mineral in the reactions between soils rich in sulfates with the Portland cements (ROLLINGS et al., 1999).

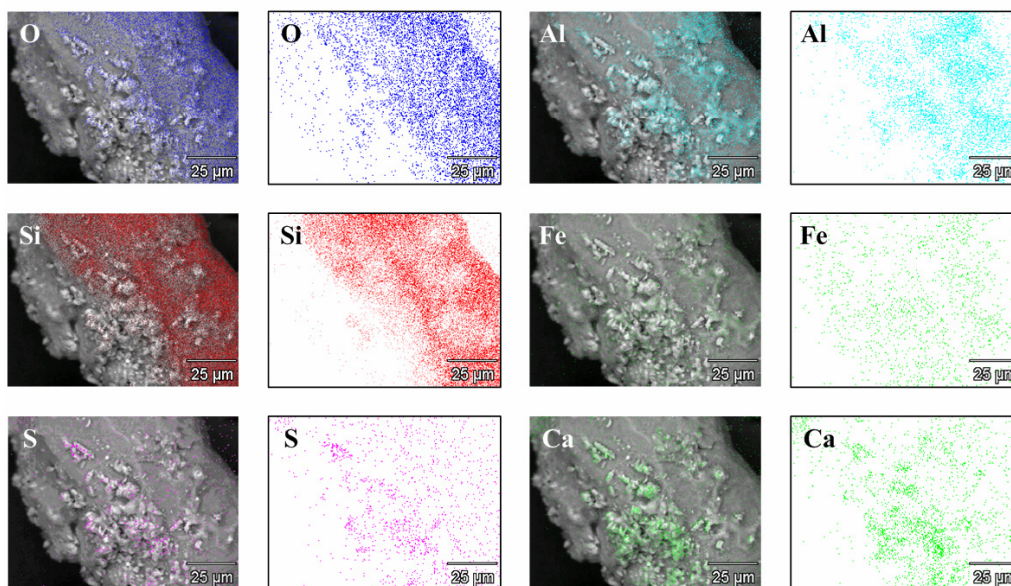


(a)

(b)



(c)



(d)

Figure 7.13. Backscattering images of the samples of: (a) soil 1 and (b) soil 1 with 6% de chemical stabilizer. Microchemicals maps of foremost important elements presents in samples of: (c) soil 1 and (d) soil 1 with 6% de chemical stabilizer.

7.4. Conclusions

- The chemical additive altered the grain size distribution of the soils. Fine particles were coalesced forming larger flakes; with tend to be granular with increasing additive content. These changes in grain size distribution are illustrated at SEM scale (secondary electron images presented in Figs. 7.9 and 7.10) showing the formation of a granular microstructure by welding of smaller particles with a cementing agent.
- Increasing chemical additive content generally caused slight increases in the PL values and decreases in the LL and PI values, as well produced small alterations in the grain unit weight of all studied soils.
- The chemical additive was responsible for significant increase in pH and CEC, with sharp reductions in the potential acidity of the soils. The pH of the mixtures reached values of 10.0, forming greater silica and aluminum solubilization in the soil, resulting in the formation of calcium silicates and aluminates. These silicates are the compounds responsible for the mechanical strength and durability of concrete from Portland cement (EADES et al., 1962). It is postulated that the inter-particle cementing matrix formed after stabilization with RBI Grade 81 is very strong and stable, and maybe be very durable.
- The OM and SEM analyses showed that increasing compaction effort accounted for the appearance of fractures along the surfaces, unconnected cracking voids in the clayey plasma (soil 1) and breaking of the quartz grains (soils 2 and 3). However, the latter effect was minimized with the addition of the chemical additive to the soils that caused the formation of highly visible cementing nuclei, especially in the soil 3 mixtures.
- Energy dispersive X-ray spectrometry (EDS) analyses indicated that contents of Si and Al oxides in soils decrease after chemical stabilization, probably by solubilization of these oxides and Ca silicates and aluminates formation during hydration and/or pozzolanic reactions of chemical stabilizer with soils.

- With reference to mineralogy, the chemical stabilizer addition resulted in peak reduction of all clay minerals and the formation of rankinite, a Ca-silicate in a well-crystalline form, easily identified by X-ray diffraction, strengthening the conclusions gotten from the EDS analyses.

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