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Reactivity of a blast furnace slag in latosols

Anelisa de Aquino Vidal Lacerda Soares[1]*, Renato de Mello Prado[2] and Fernanda de Paiva Badiz Furlaneto[1]

[1]Agência Paulista de Tecnologia dos Agronegócios, Marília, Brazil.
[2]Departamento de Solos e Adubos, Faculdade de Ciências Agrárias e Veterinárias, Universidade do Estado de São Paulo/UNESP, Jaboticabal, Brazil.

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Two experiments were conducted to study reactivity for a blast furnace slag, both developed in a greenhouse, in pots planted with *Brachiaria brizantha*. A 3 x 4 + 3 factorial was used with four replications, with three slag doses corresponding to 0.6, 1.2 and 2.4 g dm^{-3} for the clay soil and 2.2, 4.4 and 8.8 g dm^{-3} for the medium texture soil, four particle sizes (ABNT 5-10, 10-20, 20-50 and <50) and three controls (without corrective application, slag and dolomitic limestone in a dose corresponding to V=70%). In the clayey soil, there was a low efficiency of Ca and Mg release to the soil with the use of slag. It was concluded the slag, in its different particle size fractions influenced differently the pH, Ca and Mg of medium texture soil, where the fraction that passed through the ABNT 50 sieve had a greater effect on the chemical attributes evaluated. The corrective agents, slag and limestone, acted similarly on pH, Ca, Mg and V%. For greater liberation of silicon to the soil and absorption by plants it is necessary to use smaller particle sizes in the medium texture soil and intermediate particle sizes in the soil with clayey texture.

Key words: Limestone, silicate, *Brachiaria brizantha*, particle size.

INTRODUCTION

Tropical soils usually have limitations due to their high degree of acidity, affecting crop productivity (Quaggio, 2000). In this scenario, the correction of soil acidity is key to optimizing both agronomic and economic results in agriculture. The use of corrective materials such as limestone or slag can provide benefits for the agricultural sector by correcting soil acidity and providing calcium, magnesium and silicon. The availability of silicon from slag is attracting great interest in the scientific community, because it is a beneficial element that can contribute to increased crop development and production (Neto, 2009).

Currently, the same legislation applied to limestone is applied to the marketing of slag (Brasil, 2004), since both have shown similar behavior with regards to their ability to change the chemical properties of soils, as shown by other authors including Chaves and Farias (2008) and Oliveira et al. (2010).

According to legislation in Brazil about alkaline compounds, the relative reactivity (RR), which corresponds to the capacity to neutralize soil acidity over a period of three months, depends on the granulometry of these materials, that is, considers only the particle size. For the fraction larger than 2 mm (ABNT No. 10 sieve)

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*Corresponding author. E-mail: vidal@apta.sp.gov.br

Table 1. Chemical properties of the soils used in the experiment.

Texture class	pH	O.M.	Si	P	K	Ca	Mg	(H+Al)	SB	T	V
		g dm^{-3}	- mg dm^{-3}-		-----------------mmol$_c$ dm^{-3}------------------						%
Clayey	4.3	6	-	5	0.4	3	2	18	5.4	23.4	23
Medium	4.2	17	3.1	5	0.5	4	2	58	6.5	64.5	10

pH $CaCl_2$ (1:2.5); Calcium, Magnesium (KCl 1N); Potassium (Mehlich 1); Silicon $CaCl_2$ 0.01 mol L^{-1} (1:10); P resin.(Raij et al., 2001).

and smaller than 0.30 mm (ABNT No. 50 sieve) reactivity values of 0 and 100% were attributed, respectively. From these, corresponding efficiencies were assigned to the intermediate grain sizes between 2 and 0.30 mm. In calculating the reactivity of limestone, the fraction of particles retained between the ABNT 10 and 20 sieves conventionally has 20% RR and the particles retained between the ABNT 20 and 50 sieves has a RR of 60%, as indicated in legislation (Brasil, 1986).

Thus, in the case of slag, it is believed that the use of smaller particles results in greater reactivity with the soil, due to the greater surface area of the slag particle in contact with the soil (Novais et al., 1995). In a study of blast furnace slag, Oliveira et al. (1994) demonstrated that smaller particles are more effective in providing Ca and Mg to the soil than large particles. The corrective materials limestone and silicate slag are similar because both have effects on neutralization of soil acidity. However, it can be considered that rates of relative reactivity (RR) used for limestone may not express the same effect on soil chemical properties in the case of slag. This may occur because slags present a chemically and physically complex and distinct composition with respect to limestone. This difference arises from the composition of slag (calcium and magnesium silicates associated with Fe, Al and Mn compounds) and the production phase of these residues (Prado et al., 2001), because the industrial process of iron and steel extraction promotes the acquisition of various slag types with different recrystallization in function of the Ca and Mg quantities and cooling time, which can reduce their solubility (Pereira et al., 2010).

Thus, it is highlighted that the intrinsic characteristics of specific surface, such as porosity and shape of the particles, differ greatly in function of their origin. Silicates from steelmaking slag present, in general and for the same particle size, specific surface and porosity much larger than particles of a corrective material obtained from limestone (Neto, 2009). Steel slag is considered a source of silicon for different crops (rice, sugarcane and Brachiaria) (Prado et al., 2003; Pereira et al., 2004; Ramos et al., 2008; Fonseca, et al., 2009; Vidal and Prado, 2011). However, little is known regarding the interaction of different particle size fractions of the material with soils of different textures and how these fractions could affect silicon availability.

Based on the information above, a hypothesis was suggested that there are no differences in reactivity of the silicate size fractions on chemical attributes related to soil acidity and the availability of silicon. The objective was thus to study the reactivity of a blast furnace slag, in different size fractions, on chemical attributes of a dystrophic Red Latosol with clayey texture and a dystrophic Red Latosol with medium texture, cultivated with *Brachiaria brizantha*.

MATERIALS AND METHODS

The experiments were conducted in a greenhouse at the Faculty of Agricultural and Veterinary Sciences/UNESP – Jaboticabal Campus. Soil samples were collected in 0 to 20 cm depth, of a dystrophic Red Latosol with clayey texture collected in private property, near Jaboticabal city and the other of dystrophic Red Latosol with medium texture obtained in experimental farm of FCAV (Embrapa, 1999).

Physical characterization was performed according to the method proposed by Camargo et al. (1986) and the result of the dystrophic Red Latosol with clayey texture was clay: 420 g kg^{-1}, silt: 60 g kg^{-1}, fine sand: 310 g kg^{-1} and coarse sand: 210 g kg^{-1} and the dystrophic Red Latosol with medium texture was clay: 310 g kg^{-1}, silt: 90 g kg^{-1}, fine sand: 250 g kg^{-1} and coarse sand: 350 g kg^{-1}. Chemical analysis of soil for purposes of fertility followed the method described by Raij et al. (2001) and Si by calcium chloride 0.01 mol L^{-1} (Camargo et al., 2007) (Table 1).

Two corrective materials were used: one blast furnace slag with different particle sizes (total Si in hydrofluoric acid: 152 g kg^{-1}, Si soluble in NH_4NO_3 + Na_2CO_3: 4.1 g kg^{-1}, CaO: 270.7 g kg^{-1}; MgO: 48.4 g kg^{-1}; NP - neutralizing power: 604.5 g kg^{-1}, RTNP - relative total neutralization power: 443.6 g kg^{-1}) and one dolomitic limestone with original grain size (total Si: 68 g kg^{-1}, soluble Si: 0.1 g kg^{-1}, CaO: 402.3 g kg^{-1}, MgO: 58.4 g kg^{-1}, NP - neutralizing power: 865 g kg^{-1}, RTNP - relative total neutralization power: 753.2 g kg^{-1}).

The experiments were performed in one clayey soil and the other in medium texture soil. In both trials, randomized block designs were setup in a 4x3+3 factorial, with four replications. The treatments consisted of four granulometric fractions of blast furnace slag (ABNT 5-10, 10-20, 20-50 and <50), three doses of the slag corresponding to 1.25, 2.50 and 5.00 t ha^{-1}, that is, 0.6, 1.2 and 2.4 g dm^{-3} for the clay soil and 2.2, 4.4 and 8.8 g dm^{-3} for the medium texture soil. In both experiments three controls were used (limestone, blast furnace slag, without correction) at the dose corresponding to V = 70%, that is, 0.63, 2.22, 1.2 and 4.4 g dm^{-3}, respectively, for each material and soil type.

Different slag particle sizes were obtained by sieving. However, in the coarser fractions (ABNT 5-10, 10-20 and 20-50) the “dust” was removed, that is, very fine fractions of the slag to avoid possible contamination. For defining the doses the base saturation method was adopted (Raij et al., 1996), considering the RTNP value of slag and limestone. This procedure was used to compare the controls (slag and limestone), only as a preliminary evaluation and certification of the differences between materials in the soil reaction, based on the same reactivity rates adopted by legislation for limestone.

In evaluation of the factors particle size and slag doses, which was the main object of this work, a dose of 1.2 g dm^{-3} was used for the clayey texture soil and 4.4 g dm^{-3} for medium texture soil, as well as half and double these values to enable increasing doses with no intention of reaching predetermined correction levels, since determination of the slag reactivity rates is the main object of this study.

The corrective agents, at the different doses and particle sizes, were homogenized with the soil and stored for 90 days in plastic bags with moisture content maintained at 60% of field capacity using distilled water (no silicon). After the incubation period, the soils were distributed in 5 dm^3 pots that constituted the experimental units and were planted with five seedlings of *B. brizantha* cv. Marandu, previously germinated in plastic trays containing washed sand.

The basic fertilizations applied for proper development of plants were performed according to the recommendations of Mesquita et al. (2004) and Bonfim et al. (2004), followed by application of 305 mg of P dm^{-3} in the form of single superphosphate, 200 mg dm^{-3} of K (KCl p.a.), 100 mg dm^{-3} of N [NH_4NO_3 and $(NH_4)_2SO_4$ p.a.], 1.2 mg dm^{-3} of Cu ($CuSO_4.5H_2O$ p.a.), 0.8 mg dm^{-3} of B (H_3BO_3 p.a.), 1.5 mg dm^{-3} of Fe ($FeCl_3.6H_2O$ p.a.), 3.5 mg dm^{-3} of Mn ($MnCl_2.6H_2O$ p.a.), 0.15 mg dm^{-3} of Mo ($NaMoO_4.2H_2O$ p.a.) and 4 mg dm^{-3} of Zn ($ZnSO_4.7H_2O$ p.a.). At 10 days after transplantation, 50 mg dm^{-3} of N and 20 mg dm^{-3} of S [$(NH_4)_2SO_4$ p.a.] were spread on the plants.

Two plant growth cycles were evaluated. In the first cycle, the plants were cut at three months after planting, at a height of 5 cm from the ground, and the second three months after the first cutting. Soil samples were collected from the pots. They were later dried and sieved (2 mm sieve) for fertility evaluations according to the methodology proposed by Raij et al. (2001). The plant material was dried in a forced-air oven at 65°C for approximately 48 h until reaching constant weight. Then the dry mass of the plants was determined and all plant mater was ground, analyzing the concentrations of calcium and magnesium according to the methodology of Bataglia et al. (1983). Silicon in the soil was analyzed according to Camargo et al. (2007) and silicon in the plant by the methodology proposed by Bataglia et al. (1983). The results of each variable studied were submitted to analysis of variance. When the F-test was significant for interaction of the treatments, polynomial regression studies were conducted.

RESULTS AND DISCUSSION

It was observed that only particle size of the material influenced pH of the clayey soil, obtaining higher values when using the finer of the sieves (ABNT 20-50 and <50) (Table 2). The major effect of the corrective material with finer particle size on increasing the pH value was also confirmed by Pereira et al. (2010), with use of blast furnace slag 1 applied to a dystrophic Red Latosol with clayey texture, incubated for 90 days. It is highlighted that the material evaluated by these authors had similar characteristics to that used in the present study. No significant difference was observed for the doses applied and the controls (Table 2). Despite the significant interaction for pH $CaCl_2$, no polynomial regression was statistically significant (Figure 1a).

The similarity between the controls with regards to pH value, Ca and Mg, even among those that received no corrective compounds (Table 2), may be explained by the use of fertilizers containing calcium, magnesium and potassium in their formulations. These were applied at planting and in coverage during the assays, noting that the fertilizers to nourish the plants were the same in all treatments, differing only with regards to the corrective compound utilized particle size and dosage. Unlike the clayey soil, increases in $CaCl_2$ pH were observed with the slag doses, where 8.8 g dm^{-3} was the dose presenting the highest pH value (Table 2). Similar to the results obtained, Neto (2009) studied the relative efficiency of different particle size fractions of silicates on the correction of acidity for soils ranging from clayey to sandy and found a large variation in pH for soils of medium texture after application of corrective doses. Thus, it was emphasized that the clayey soils, in comparison with medium texture and even sandy soils, have a higher buffering capacity and hence greater resistance to variations in pH (Furtini et al., 2001).

Use of the finer particle size also favored an increase in pH $CaCl_2$, where the material retained on the sieve ABNT <50 presented the highest values (Table 2). No significant difference was observed between the controls. The same behavior was observed by Neto (2009) who found that at 30 and 90 days after the incubation of three calcium silicates and one limestone sample in a typical dystrophic Red Latossol of medium texture, smaller particle sizes of the corrective material resulted in greater increases of pH $CaCl_2$ values.

Behavior similar to that of pH $CaCl_2$ was observed for magnesium in soil with regards to the doses applied (Table 2). Santana et al. (2010) also reported the effect of limestone and silicate slag application on chemical attributes of the soil, and production and quality of brachiaria forage; increases in soil magnesium were also observed in function of the corrective levels, after application of slag.

The doses of 0.6 and 1.2 g dm^{-3} showed the highest concentrations of calcium and the dose of 0.6 g dm^{-3} resulted in the highest concentration of magnesium in the clayey soil (Table 2). There was also increased calcium concentration in soil of the treatment with particle size ABNT 10-20 and magnesium in the treatment with particle size ABNT <50. Considering the interaction of factors (Figure 1b and c), the slag dose provided in each particle size treatment reduced the availability of calcium and magnesium in the soil. Similarly, Pereira et al. (2010) noted low efficiency of two blast furnace slags (AF1 and AF2) with regards to available calcium and magnesium in a dystrophic Red Latosol, at a dose of 1500 mg kg^{-1} of $CaCO_3$ equivalent, independent of the particle size fraction used. Concordance verified among the controls with regards to chemical alterations of the clayey soil indicated that both the limestone and slag showed the same behavior for neutralization of soil acidity, availability of Ca^{2+} and Mg^{2+}, and V% after three months of

Table 2. Results of pH, Ca, Mg, V and Si in the soil after application of blast furnace slag and limestone to two soils – 1st cutting.

Treatment	pH $CaCl_2$	Ca^{+2}	Mg^{+2}	V	Si
		$mmol_c\ dm^{-3}$		%	$mg\ dm^{-3}$
Dystrophic Red Latosol – clayey texture					
Slag doses (D) (g dm^{-3})					
0.6	5.7	69.1 ^{a}	2.6 ^{a}	73	6.4
1.2	5.8	66.4 ^{a}	1.9 ^{b}	76	6.8
2.4	5.8	59.2 ^{b}	2.4 ^{ab}	75	6.9
Dms	0.18	5.61	0.63	4.07	0.85
Different particle sizes of the blast furnace slag (G)					
ABNT 5-10	5.6 ^{c}	56.9 ^{c}	1.2 ^{c}	71 ^{b}	6.2
ABNT 10-20	5.7 ^{bc}	72.6 ^{a}	2.0 ^{bc}	74 ^{ab}	6.6
ABNT 20-50	5.9 ^{a}	67.6 ^{ab}	2.3 ^{b}	77 ^{a}	7.1
ABNT <50	5.8 ^{ab}	62.6 ^{bc}	3.7 ^{a}	76 ^{a}	6.9
Dms	0.23	7.13	0.80	5.18	1.08
Controls					
Limestone	5.9	58.5	2.7	74	7.4ab
Slag	6.0	62.7	1.7	73	8.2a
No correctives	5.6	62.7	1.5	71	6.3b
Dms	0.23	11.2	1.2	8.15	1.70
F-Test					
Test x Trat	0.41^{ns}	3.30 ^{ns}	1.72^{ns}	1.81 ^{ns}	3.35^{ns}
Between Tests	3.05 ^{ns}	0.48 ^{ns}	3.20*	0.34 ^{ns}	3.80*
Doses	0.76 ^{ns}	9.90**	3.55*	2.25 ^{ns}	1.11 ^{ns}
Particle sizes	4.43 **	12.67**	22.42**	3.61*	1.63 ^{ns}
D x G	2.42*	8.45**	9.45**	3.72 **	1.21 ^{ns}
C.V.(%)	3.66	10.19	32.84	6.40	14.55
Dystrophic Red Latosol – medium texture					
Slag doses (D) (g dm^{-3})					
2.2	5.4 ^{b}	77.5 ^{a}	2.6 ^{b}	70 ^{b}	5.3 ^{b}
4.4	5.6 ^{ab}	73.0 ^{a}	3.0 ^{b}	73 ^{b}	6.1 ^{b}
8.8	5.8 ^{a}	67.2 ^{b}	7.2 ^{a}	79 ^{a}	7.4 ^{a}
Dms	0.20	5.57	0.83	4.07	0.95
Different particle sizes of the blast furnace slag (G)					
ABNT 5-10	5.4 ^{b}	57.1 ^{b}	1.5 ^{c}	67 ^{b}	4.9 ^{b}
ABNT 10-20	5.6 ^{ab}	81.2 ^{a}	6.3 ^{a}	74 ^{a}	6.1 ^{b}
ABNT 20-50	5.6 ^{ab}	75.3 ^{a}	6.4 ^{a}	78 ^{a}	6.0 ^{b}
ABNT <50	5.8 ^{a}	76.7 ^{a}	2.7 ^{b}	77 ^{a}	7.9 ^{a}
Dms	0.26	7.08	1.06	5.87	1.21
Controls					
Limestone	5.6	72.0 ^{a}	2.3 ^{b}	72 ^{a}	5.4
Slag	5.6	79.5 ^{a}	4.2 ^{a}	78 ^{a}	5.7
No correctives	5.2	54.7 ^{b}	1.5 ^{b}	59 ^{b}	4.2
Dms	0.41	11.14	1.67	9.23	1.91
F-Test					

Table 2. Results of pH, Ca, Mg, V and Si in the soil after application of blast furnace slag and limestone to two soils – 1st cutting. (Contd.).

Test x Trat	2.43^{ns}	3.31 ^{ns}	25.21**	5.99*	9.96**
Between Tests	3.36*	15.29**	8.47**	0.34 ^{ns}	2.00 ^{ns}
Doses	8.79**	10.15**	109.25**	2.25 ^{ns}	14.54**
Particle sizes	7.32**	32.10**	78.96**	3.61*	15.07**
D x G	2.60*	7.74**	25.52**	3.72 **	3.79**
C.V. (%)	4.36	9.04	24.84	6.40	18.50

Means followed by the same lower-case letter in the same column indicate no significant difference by the Tukey test (p< 0.5).

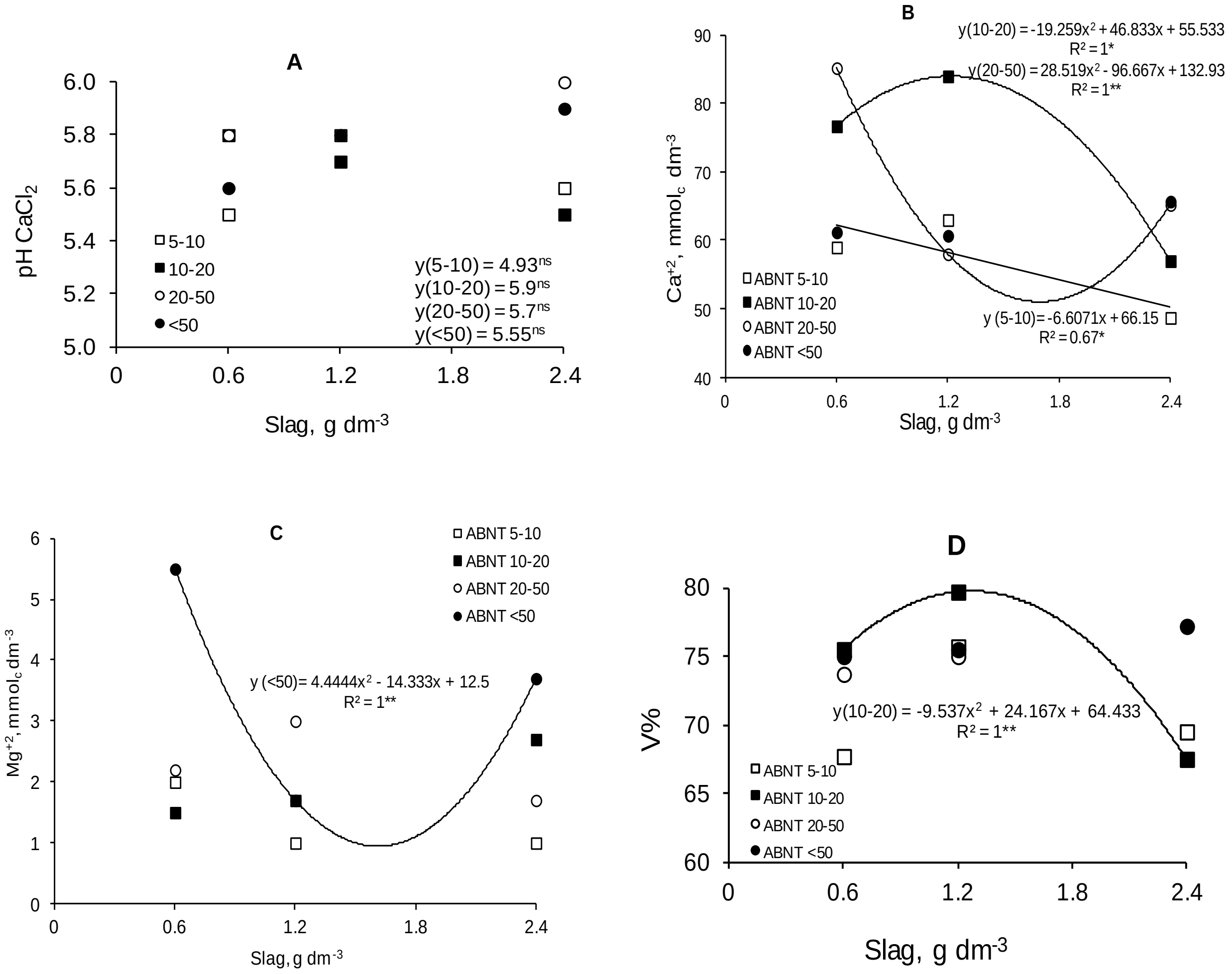

Figure 1. Values of pH CaCl$_2$(A), calcium(B), magnesium(C) and base saturation(D) in dystrophic Red Latosol with clayey texture, in function of the slag doses and particle sizes evaluated – 1st cutting (** $p<0.01$; * $p<0.05$; ^{ns} – non-significant).

cultivation (Table 2), although the materials (silicate and carbonate) are chemically different.

Considering the indications of similarities between the two corrective compounds (silicate and carbonate) and the observations made by Pulz et al. (2008), when considering the influence of calcium and magnesium silicate compared to dolomitic lime with regards to nutrition, productivity and quality of potatoes under water stress conditions, it was also noted that the Ca and Mg silicates resulted in the same levels of soil correction and supply of these nutrients as dolomitic lime, thus permitting that it be used to substitute limestone.

In the case of limestone, with a decrease in particle size there was greater availability of calcium in the medium texture soil (Table 2). However, for magnesium the intermediate sieves (ABNT 10-20 and 20-50) were responsible for the highest values of this element in the soil. Therefore, Deus et al. (2014) indicated that the smaller the particle size of the corrective materials, high was the availability of calcium due to increased contact of the material with the soil, resulting in higher specific surface area and thus greater solubility. Regarding the controls, the treatment receiving slag presented higher magnesium availability in soil and both were similarly able to provide calcium to the soil. For base saturation data, the particle size influenced this result (Table 2). It was verified that application of the first dose (0.6 g dm^{-3}) was sufficient to achieve the V% recommended for *B. brizantha*. It was also observed that the material retained in the ABNT 5-10 sieve showed the lowest V% compared to the other sieves. This last result may be validated by the observations made by Prado et al. (2004) who found a decrease in efficiency of steel slag to increase base saturation of a dystrophic Red Latosol as the particle size of the material became coarser. The interaction between the two factors studied was significant only for the particle size of 10 to 20 (Figure 1d) and contributed to the increase in base saturation only up to a dose of 1.2 g dm^{-3} of slag. An increase in V% was noted for the doses with decrease in particle size of the slag in medium texture soil (Table 2). Among the controls, both limestone and slag obtained V% values higher than the absolute control.

The shoot dry mass varied according to the doses and particle size of the slag, being higher for the dose of 1.2 g dm^{-3} which was calculated to reach a base saturation equivalent to 70% (recommended for *B. brizantha*) and for the particle sizes of 10-20 and 20-50 (Table 3). The sieves with coarser (ABNT 5-10) and finer mesh (ABNT <50) indicated the lowest production, while the corrective materials used in the experiment with original particle size (limestone and slag) showed the same behavior. There was no difference from the control without corrective. From the interaction between the factors evaluated, it was found that increasing the slag doses for the particle sizes of 5-10 and 20-50 resulted in a reduction of the plant dry mass (Figure 2a). These results can be explained by the observations made by Oliveira et al. (2000) when studying the effect of soil fertility correction on the development of *B. brizantha* cv. Marandu in a Latosol. The authors reported that these plants have little response of dry matter production after correction of soil acidity, attributing this behavior to the intrinsic tolerance of these plants to the components that make up soil acidity and good adaptability to soils poor in nutrients.

The calcium content in the shoots was not affected by the treatments, probably because in all situations calcium is within the proper range, which according to Malavolta (1992) varies from 1.5 to 6.0 g kg^{-1} (Table 3). However, the magnesium content was higher in the doses of 1.2 and 2.4 g dm^{-3} of slag. The finer particle sizes of the slag resulted in higher magnesium content in the plant shoots in accordance with the increased availability of soil nutrients under the same conditions. Analyzing the interactions, it was noted that for both calcium (Figure 2b) and magnesium (Figure 2c), the slag doses in the finer particle sizes increased levels in the plants.

In the soil with clayey texture, Si contents in the soil and plant did not differ as a function of the dose and particle size of the corrective material employed (Tables 2 and 3). In turn, Pereira et al. (2004) highlighted that blast furnace slag is less reactive than steel slag, and for increase silicon release to the soil from blast furnace slag it is necessary to use smaller particle sizes <0.3 mm. However, Prado et al. (2001) emphasized that the slag is a more abrasive material than limestone, reporting that Brazilian mills do not have the technical and economic capacity to grind this residue to such a small size, beyond that commonly used for limestone. Among the controls, slag showed higher availability of silicon in the soil compared to limestone and the control without correction, due to the chemical composition of the slag in the present study of 4.1 g kg^{-1} of soluble Si (Table 2). It was also observed that the interactions were not significant between the slag doses applied and particle size for the variables of silicon in the soil and the plants (Tables 2 and 3). For the medium texture soil (Table 3), the factors of slag dose and particle size did not influence production of plant dry mass. However, among the means it was observed that slag application resulted in increased dry mass in comparison with limestone and the absolute control. When analyzing silicon in the soil, it can be observed that both the largest as well as the finest particle sizes of the material resulted in greater availability of the element (Table 2) (Figure 3e). In the plant, it was observed that despite the increase in availability of this element in the soil with the slag doses, there was no significant difference of the levels in the plant. For the particle size evaluations, it was found that the greater availability of Si in the soil was obtained in the treatment with the sieve ABNT <50, that is, in the finer material of this treatment, where a higher Si content in the plant was observed. Comparing the behavior of the soils with regards to reactivity of the slag, the medium texture soil favored reaction of the material compared to the clayey soil.

The interactions were significant for pH, Ca, Mg, V% and Si in the soil with medium texture and calcium in the plant (Figure 3a, b, c, d, e). After six months of conducting this test, the effects of dose and particle size were verified on the concentrations of Mg, V% and Si in the soil (Table 4). The alteration of Mg^{2+} was directly reflected in base saturation, but without great efficiency to differentiate the effects of each particle size in this evaluation, thus disagreeing with the findings of Natale and Coutinho (1994) and Prado et al. (2004) with regards to greater base saturation in discriminating the efficiency of the limestone and slag size fractions, respectively.

Table 3. Dry mass, contents of calcium, magnesium and silicon in the plant, after application of the blast furnace slag and dolomitic lime in two soils – 1st cutting.

Treatment	**Dry mass**	**Ca**	**Mg**	**Si**
	g per pot	**-------g kg^{-1}---------**		
	dystrophic Red Latosol – clayey texture			
Slag doses (D) (g dm^{-3})				
0.6	28.4 ^{ab}	6.5	3.0 ^{b}	8
1.2	31.0 ^{a}	7.0	3.8 ^{a}	8
2.4	24.6 ^{b}	6.5	3.7 ^{a}	8
Dms	4.67	0.98	0.42	0.19
	Different particle sizes of the blast furnace slag (G)			
ABNT 5-10	24.5 ^{b}	7.0	3.1 ^{c}	8
ABNT 10-20	33.8 ^{a}	6.3	3.3 ^{bc}	8
ABNT 20-50	29.3 ^{ab}	6.8	4.0 ^{a}	8
ABNT <50	24.3 ^{b}	6.8	3.6 ^{ab}	8
Dms	5.94	1.24	0.54	0.24
Controls				
Limestone	26.8	6.5	3.6	8
Slag	23.6	6.3	3.6	10
No corrective	24.1	5.9	3.1	9
Dms	9.34	1.96	0.85	0.38
	F-test			
Test x Trat	3.20^{ns}	1.79 ^{ns}	0.11 ^{ns}	1.17^{ns}
Between Tests	0.41^{ns}	0.28 ^{ns}	1.10 ^{ns}	0.31^{ns}
Doses	5.56**	0.91 ^{ns}	10.19**	0.45^{ns}
Particle sizes	8.20**	0.86 ^{ns}	7.32**	0.09^{ns}
D x G	3.94**	3.20 *	8.40**	2.15^{ns}
C.V.(%)	19.89	17.24	14.12	26.81
	Dystrophic Red Latosol – medium texture			
	Slag doses (D) (g dm^{-3})			
2.2	21.4	6.7 ^{b}	3.4 ^{b}	7.7
4.4	23.5	7.2 ^{ab}	3.7 ^{ab}	8.1
8.8	24.6	7.4 ^{a}	4.1 ^{a}	8.3
Dms	4.24	0.75	0.64	0.1
	Different particle sizes of the blast furnace slag (G)			
ABNT 5-10	18.9	7.3	2.67 ^{c}	8.0 ^{ab}
ABNT 10-20	21.9	7.1	3.0 ^{bc}	6.8 ^{b}
ABNT 20-50	23.4	7.0	3.7 ^{b}	7.9 ^{ab}
ABNT <50	23.8	6.9	5.5 ^{a}	9.4 ^{a}
Dms	5.40	0.95	0.81	0.2
	Controls			
Limestone	21.2 ^{ab}	7.8 ^{a}	5.4 ^{a}	6.5 ^{b}
Slag	25.6 ^{a}	6.3 ^{ab}	5.4 ^{a}	9.7 ^{a}
No corrective	15.7 ^{b}	5.2 ^{b}	2.7 ^{b}	6.5 ^{b}
Dms	8.49	1.50	1.28	6.5 ^{b}
	F-test			
Test x Trat	0.56^{ns}	5.40*	10.49**	0.73^{ns}

Table 3. Contd.

Between Tests	3.98*	8.57**	18.06**	5.07*
Doses	1.18ns	3.20*	3.77*	0.59ns
Particle sizes	2.44ns	0.42 ns	35.03**	4.85**
D x G	1.12ns	5.82 *	1.55ns	2.26ns
C.V.(%)	22.71	12.57	19.12	20.96

Means followed by the same lower-case letter, in the same column, indicate no significant difference by the Tukey test (p< 0.5).

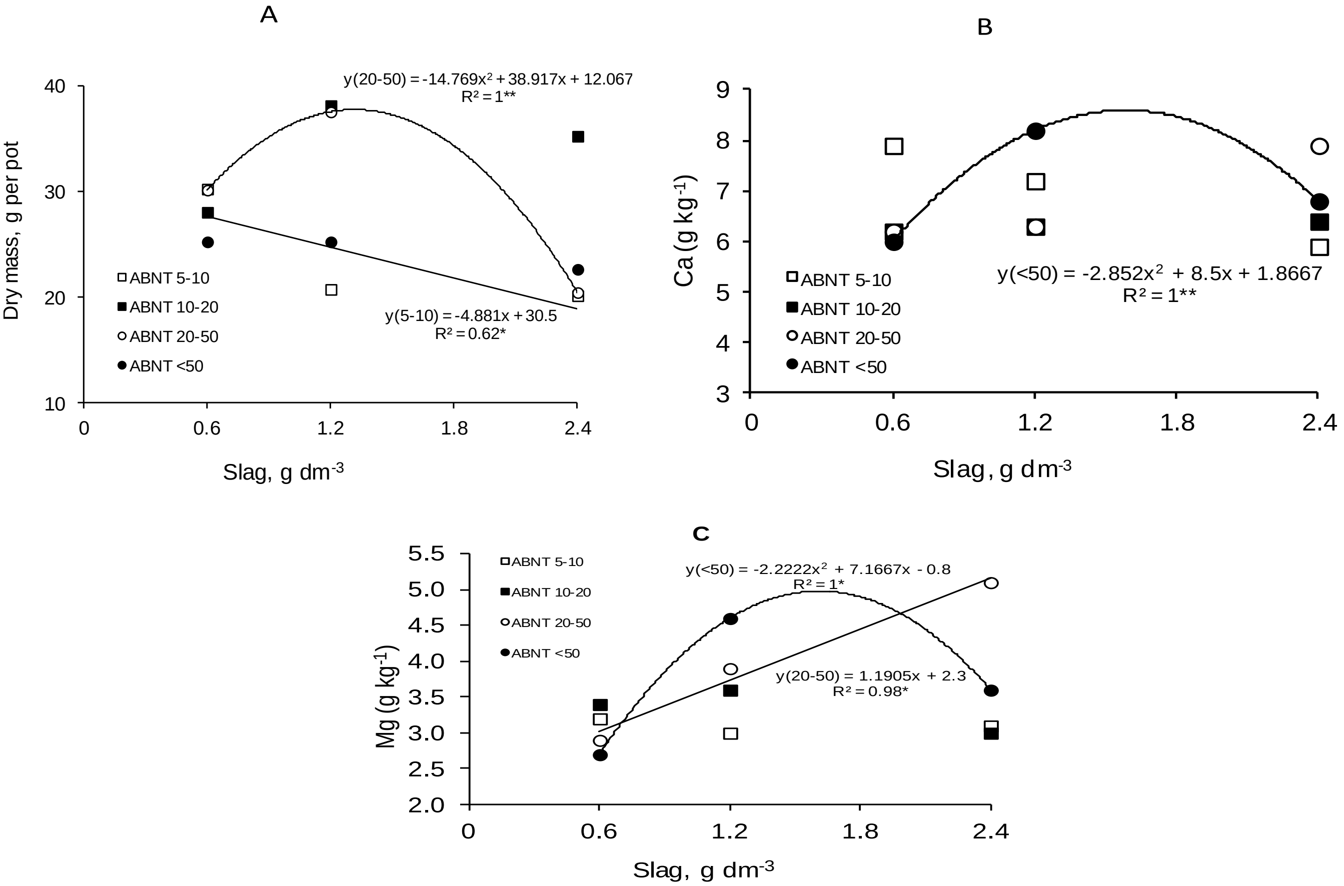

Figure 2. Dry mass (A) and concentrations of calcium (B) and magnesium (C) in plants of *B. brizantha* in function of the slag doses and particle size fractions in dystrophic Red Latosol with clayey texture – 1st cutting (** $p<0.01$; * $p<0.05$; ns – non-significant).

It was also highlighted that although the results of base saturation found in this study are inefficient in discriminating the reaction of the different slag size fractions, this variable becomes important because the pH was not influenced by the different particle sizes. Moreover, base saturation is presented as an additional practical benefit, since one of the liming methods is based on the V% value (Prado et al., 2004).

With respect to silicon in clayey soil, a greater reaction of slag was observed at six months after planting *Brachiaria brizantha* (Table 4). It was found that increasing the doses and the finer particle size fractions resulted in the highest Si concentrations in the soil (Figure 4e), corroborating with the results of Neto (2009), who observed that at 90 days of incubation the differences between the blast furnace slag particle sizes for Si concentrations were greater in relation to 30 days in a clayey soil.

It was found that although the doses influence Si availability in the soil, they did not interfere with its

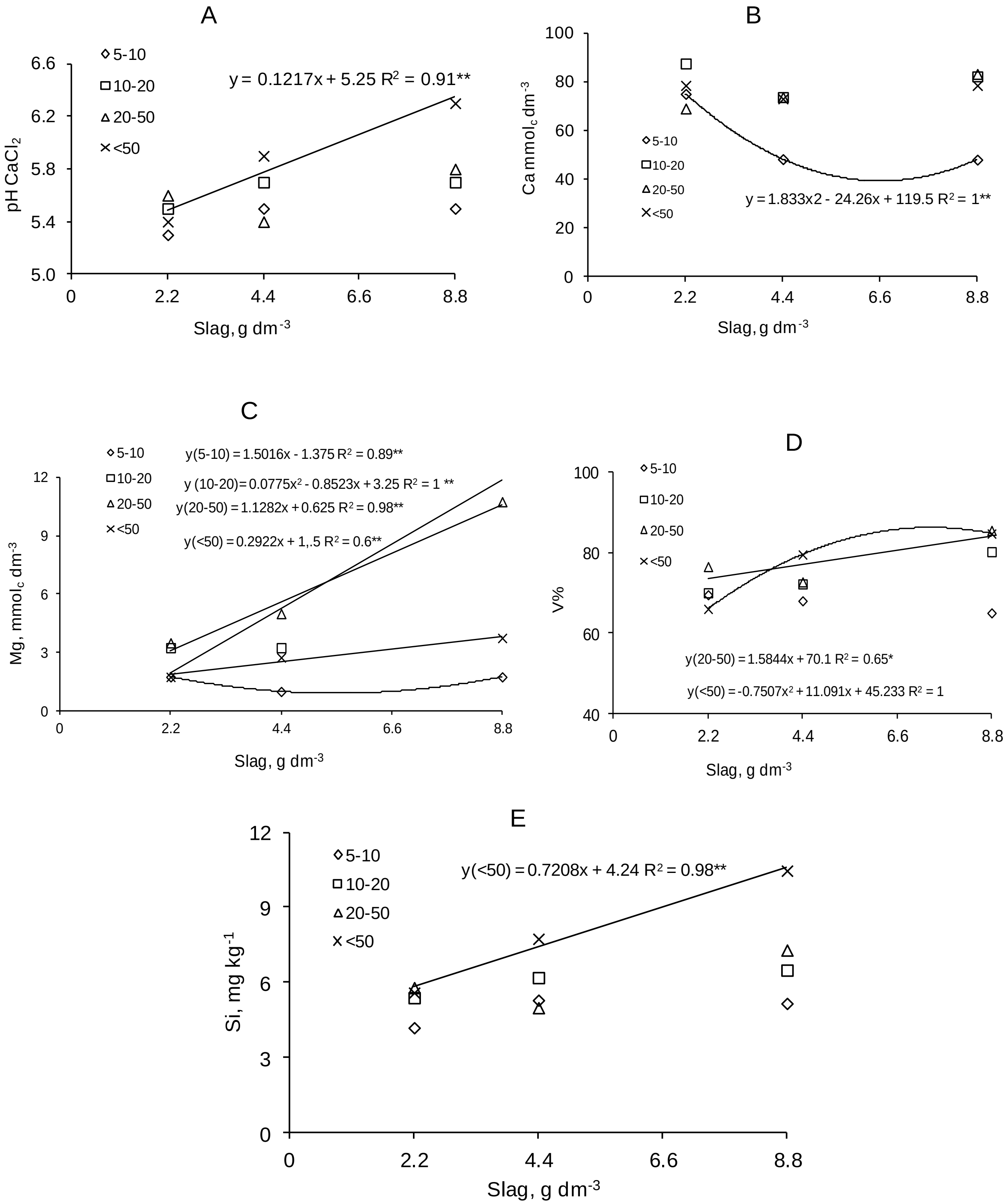

Figure 3. Effect of slag doses and particle size fractions on pH $CaCl_2$ (A) value, calcium (B), magnesium (C), V% (D) and available silicon (E) in dystrophic Red Latosol with medium texture – 1^{st} cutting (** $p<0.01$; * $p<0.05$; ^{ns} – non-significant).

concentration in the plant (Table 4). The opposite effect was observed by Fonseca et al. (2009) when studying the behavior of slag, limestone and nitrogen in silicon absorption and production of marandu grass after application of corrective doses, finding that in the second cutting of the plants the Si content in the plant material

Table 4. Dry mass, pH, Ca, Mg, V and Si in the soil and plants after application of the blast furnace slag and limestone in the two soils – 2nd cutting.

Treatment	Dry mass	pH $CaCl_2$	Ca^{+2}	Mg^{+2}	V	Soil Si	Plant Si
	g per pot		mmol$_c$ dm^{-3}		%	mg kg^{-1}	g kg^{-1}
Dystrophic Red Latosol – clayey texture							
Slag dose (D) (g dm^{-3})							
0.6	15.6	5.6	65.3	1.4 ^{b}	73.8 ^{b}	6.5 ^{b}	10.5
1.2	14.8	5.7	65.0	1.7 ^{b}	77.0 ^{a}	6.5 ^{b}	9.8
2.4	14.7	5.7	60.1	2.6 ^{a}	74.7 ^{ab}	7.3 ^{a}	9.7
dms	2.05	0.15	5.76	0.38	2.63	0.55	1.4
Different particle sizes of the blast furnace slag (G)							
ABNT 5-10	15.5	5.6	53.5	1.3 ^{b}	72.2 ^{b}	5.8 ^{b}	10.2 ^{ab}
ABNT 10-20	14.4	5.6	71.2	1.9 ^{a}	75.0 ^{ab}	6.9 ^{a}	11.0 ^{a}
ABNT 20-50	14.3	5.8	64.3	2.2 ^{a}	77.2 ^{a}	7.2 ^{a}	10.0 ^{ab}
ABNT <50	16.0	5.8	64.9	2.2 ^{a}	76.2 ^{a}	7.1 ^{a}	8.9 ^{b}
dms	2.61	0.19	7.33	0.49	3.35	0.70	1.8
Controls							
Limestone	15.1	5.8 ^{a}	49.7 ^{ab}	2.2	77.5	7.8 ^{a}	11.5 ^{a}
Slag	17.2	5.7 ^{a}	55.0 a	2.2	75.0	8.4 a	11.7 ^{a}
dms	4.15	0.19	12.11	0.64	4.37	1.11	2.93
F-test							
Test x Trat	2.87 ^{ns}	3.58 ^{ns}	40.40 **	3.78 ^{ns}	0.83 ^{ns}	9.39**	0.46 ^{ns}
Among Tests	0.79 ^{ns}	11.31**	3.30 *	0.00 ^{ns}	1.34 ^{ns}	15.12**	15.73 **
Doses	0.61 ^{ns}	0.42 ^{ns}	2.72 ^{ns}	32.68 **	4.49 *	9.01**	1.12 ^{ns}
Particle sizes	1.45 ^{ns}	3.90 ^{ns}	12.97 **	10.20**	5.72 **	12.89**	3.04 *
D x G	3.60**	4.00**	8.58 **	14.34**	11.06**	3.37**	7.74**
C.V.(%)	15.84	3.2	11.65	22.8	4.06	9.33	17.17
Dystrophic Red Latosol – medium texture							
Slag dose (D) (g dm^{-3})							
2.2	16.2	5.3 ^{b}	69.5	2.5 ^{b}	71.1 ^{c}	5.4 ^{c}	8.6 ^{b}
4.4	17.3	5.6 ^{a}	71.7	3.4 ^{b}	75.2 ^{b}	6.3 ^{b}	10.5 ^{a}
8.8	17.0	5.7 ^{a}	79.2	7.5 ^{a}	79.4 ^{a}	7.5 ^{a}	11.7 ^{a}
dms	1.94	0.20	11.19	1.12	3.56	0.49	1.44
Different particle sizes of the blast furnace slag (G)							
ABNT 5-10	14.9 ^{b}	5.3 ^{b}	58.5 ^{b}	1.3 ^{c}	67.6 ^{b}	4.9 ^{d}	8.0 ^{b}
ABNT 10-20	17.6 ^{a}	5.5 ^{ab}	63.1 ^{b}	6.1 ^{a}	76.2 ^{a}	5.9 ^{c}	11.2 ^{a}
ABNT 20-50	17.2 ^{ab}	5.6 ^{ab}	82.7 ^{a}	7.4 ^{a}	77.4 ^{a}	6.6 ^{b}	10.6 ^{a}
ABNT <50	17.6 ^{a}	5.7 ^{a}	89.7 ^{a}	3.0 ^{b}	79.7 ^{a}	8.0 ^{a}	11.4 ^{a}
dms	2.47	0.25	14.24	1.43	4.53	0.63	1.83
Controls							
Limestone	17.3 ^{ab}	5.5	61.2 ^{ab}	4.0	71.2	5.4 ^{ab}	7.7 ^{ab}
Slag	19.7 ^{a}	5.6	80.0 ^{a}	4.2	76.7	5.8 ^{a}	10.5 ^{a}
dms	3.94	0.40	22.39	1.86	5.92	0.99	2.88
Teste de F							
Test x Trat	0.94 ^{ns}	4.51 *	3.84 ^{ns}	0.45 ^{ns}	0.62 ^{ns}	38.16**	3.39 ^{ns}
Among Tests	3.26 *	2.18 ^{ns}	4.10*	0.07 ^{ns}	3.53 ^{ns}	5.89**	5.50*

Table 4. Contd.

Doses	1.10 ^{ns}	11.82**	2.45 ^{ns}	66.92**	16.12**	54.47**	13.96**
Particle sizes	3.78 *	6.07**	16.00**	54.64**	19.76**	60.42**	10.72**
D x G	0.70 ^{ns}	3.20*	2.25^{ns}	15.33**	1.50 ^{ns}	15.85**	3.86**
C.V	13.52	4.27	18.15	29.60	5.52	9.39	16.38

Means followed by the same lower-case letter, in the same column, indicate no significant difference by the Tukey test (p< 0.5).

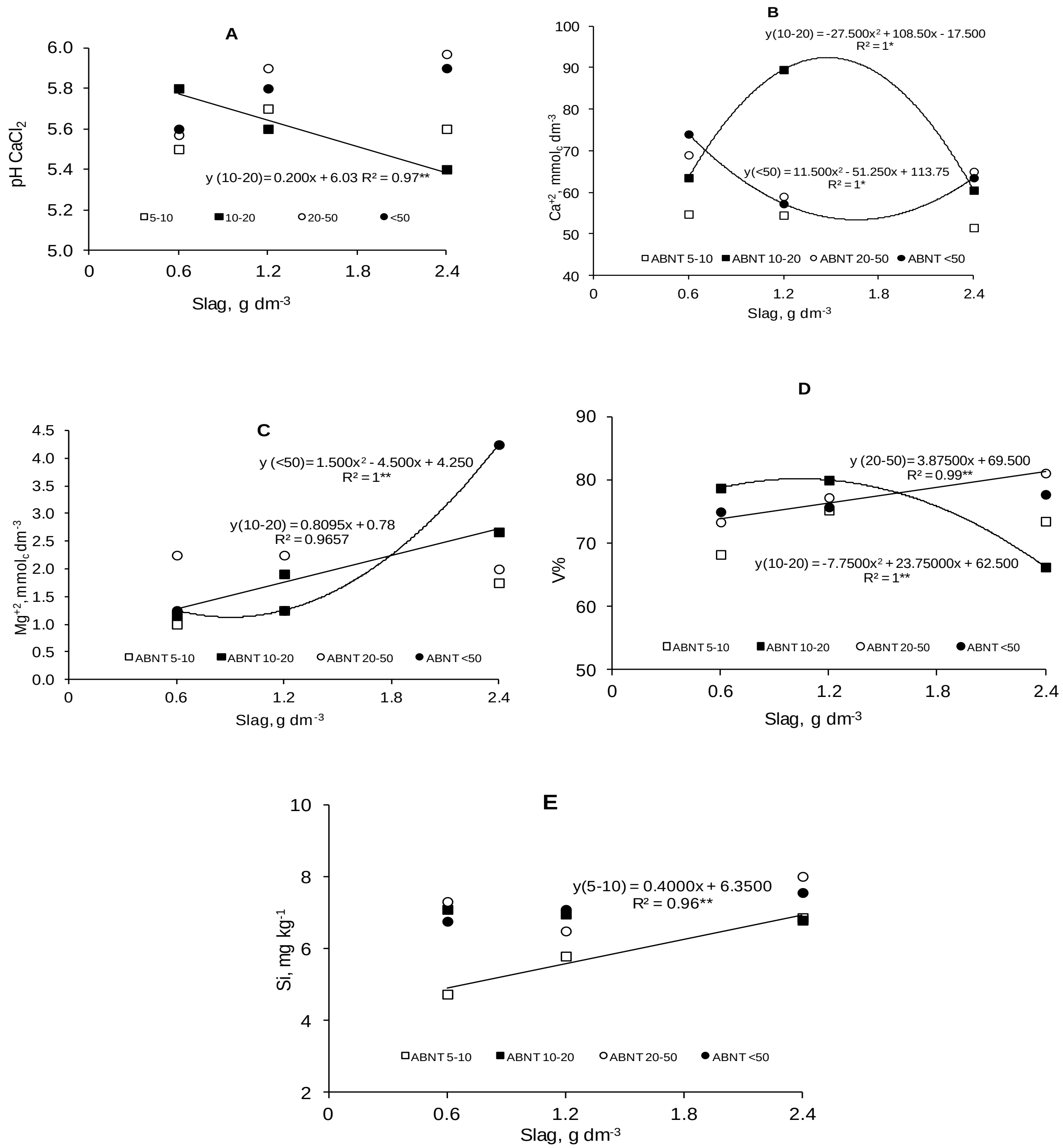

Figure 4. Effect of the slag doses and particle size fractions on the pH $CaCl_2$ value (A), calcium (B), magnesium (C), V% (D) and available silicon (E) in a dystrophic Red Latosol with clayey texture – 2nd cutting.

increased with the silicate doses. It was also observed that the intermediate particle sizes decreased dry mass (Figure 5a) and the finer particle sizes favored higher silicon contents in the leaves of brachiaria (Figure 5b).

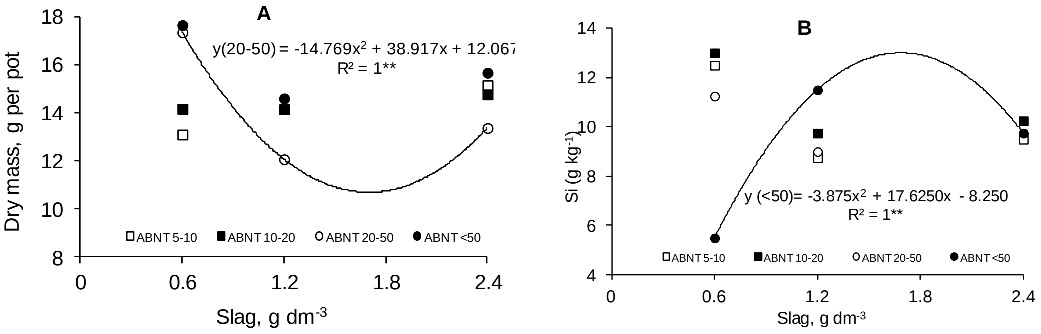

Figure 5. Dry mass (A) and silicon (B) content in plants according to the slag doses and particle size fractions of a dystrophic Red Latosol with clayey texture - 2nd cutting.

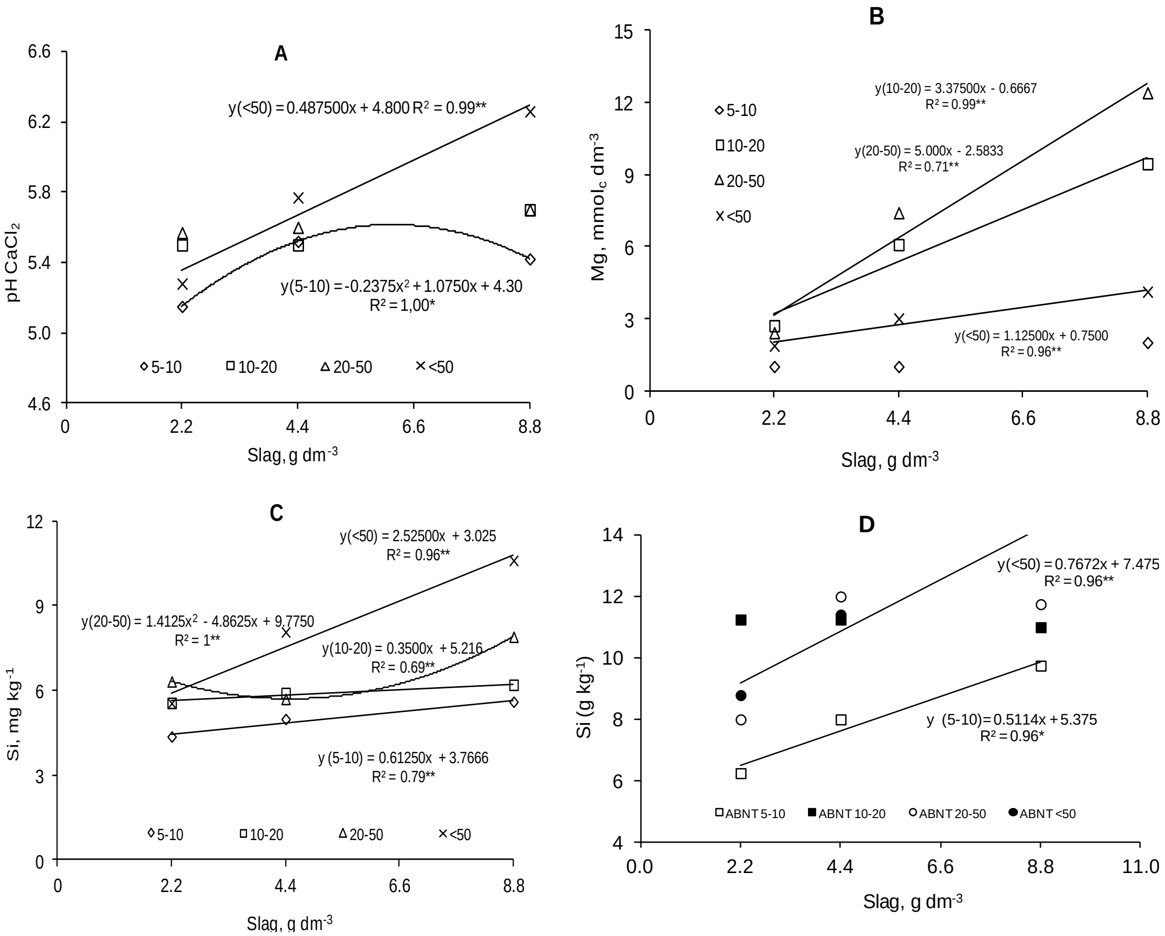

Figure 6. Effect of the slag doses and particle size fractions on values of pH $CaCl_2$ (A), magnesium (B) and available silicon (C) for a dystrophic Red Latosol with medium texture, and silicon (D) content in the plant shoots – 2nd cutting.

The slag doses influenced the pH $CaCl_2$, Mg^{+2} and V% of the soil, as well as the availability of Si in the soil and the plant (Table 4). Unlike clayey soil, the greater availability of Si in the soil provided by the slag doses also favored the higher content of this element in the plant. Table 4 shows the behavior of particle size after six months of *B. brizantha* cultivation in a soil of medium texture on the variables studied. The finer particle size (ABNT <50) resulted in the highest dry matter yield as well as the highest values of pH $CaCl_2$, Ca^{+2}, Mg^{+2}, V% and Si in the soil and the plant (Figure 6a, b, c, d).

Evaluating the interactions of the factors studied

(Figure 6a), only the coarsest (ABNT 5-10) and finest particle sizes (ABNT <50) influenced pH $CaCl_2$ in function of the slag doses, indicating that these fractions, even after 90 days of incubation with the soil and another 60 days of brachiaria cultivation, continued reacting and solubilizing. However, for the coarser particle sizes, with application of the highest dose (8.8 g dm^{-3}) there was a tendency to reduce its effect on pH. For magnesium (Figure 6b), only the coarsest particle size did not show a mathematical fit for the availability of this nutrient in the soil as a result of slag doses, favoring larger nutrient quantities in the soil.

All particle sizes in function of slag levels influenced the availability of silicon to the soil (Figure 6c). It is important to highlight that the greater the sieve mesh size, the greater the availability of Si to the soil, even with the increasing doses applied. On the other hand, only for the particle sizes ABNT 5-10 and <50 was a mathematical adjustment obtained which represented Si uptake by the plants as a function of slag levels (Figure 6d).

Conclusion

Blast furnace slag, in its different particle size fractions, differently influenced the pH, Ca and Mg of medium texture soil, where the fraction that passed through the ABNT 50 sieve had the greatest effect on the chemical attributes evaluated. The corrective materials, blast furnace slag and limestone, act similarly on pH, Ca, Mg and V%. For greater liberation of silicon to the soil and absorption by plants it is necessary to use smaller particle sizes (<0.3 mm) in soil with average texture and intermediate sizes (0.85 to 1.41) in soil with clayey texture.

Conflict of Interest

The authors have not declared any conflict of interest.

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