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Reutilization of granite powder as an amendment and fertilizer for acid soils

M.T. Barral Silva ^{a,*}, B. Silva Hermo ^a, E. García-Rodeja ^b, N. Vázquez Freire ^a

^a Departamento de Edafología y Química Agrícola, Facultad de Farmacia, Universidad de Santiago, Santiago de Compostela 15782, Spain

^b Departamento de Edafología y Química Agrícola, Facultad de Biología, Universidad de Santiago, Santiago de Compostela 15782, Spain

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Abstract

The properties of granite powders—a granite manufacturing waste product—were analyzed to assess their potential use as amendments and fertilizers on acid soils. Two types of powders were characterized: one produced during cutting of granite with a diamond-edged disc saw, comprising only rock powder, the other produced during cutting with a multi-blade bandsaw, containing calcium hydroxide and metal filings added during the cutting procedure. The acid neutralizing capacity of the granite powders was assessed in short- (2–3 h) and medium-term (1–30 d) experiments. The powders showed a buffering capacity at around pH 8, which corresponded to the rapid dissolution of basic cations, and another buffering effect at pH < 4.5, attributable to the dissolution of Fe and Al. The acid neutralizing capacity (ANC) determined in the short-term experiments, to a final pH of 4.5, varied between 5 and 61 cmol H⁺ kg⁻¹ powder. The ANC to pH 4.5 obtained in the medium-term experiments was much higher than that obtained in the short-term experiments, reaching a maximum ANC value of 200 cmol H⁺ kg⁻¹ powder. There was no great difference in the neutralizing capacity determined at between 1 and 30 d.

The most abundant elements in acid solutions obtained at the end of medium-term experiments were Mg and Ca for disc saw powders, whereas Ca and Fe (at pH < 5) were the most soluble elements in the bandsaw powders. The rapid release of these cations suggests the possible effective use of the granite powders as a source of nutrients on being added to acid soils.

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1. Introduction

During granite manufacturing a waste product, known as granite powder or granite dust, is produced. Disposal of the product is a serious problem for the production companies because of the large volume

^{*} Corresponding author. Tel.: +34 981 563 100; fax: +34 981 594 912.

E-mail address: edbarral@usc.es (M.T. Barral Silva).

generated and because until now no viable method of reusing the product has been developed.

The granite industry in Spain is one of the most important in the world and the most important in Europe. More than 90% of the national production is produced in Galicia (northwest Spain). In recent years there has been a large expansion of the granite processing industry in Galicia, and the exportation of granite blocks has been superseded by the exportation of manufactured products, leading to an increase in the volume of granite powder produced.

The processing of natural stone extends from the moment at which the quarried block arrives at the manufacturing workshop until it is transformed into a finished product. The first stage of the process involves cutting the block into slabs. There are two main methods of cutting granite. In the first method, the blocks are cut using large discs that are edged with diamond segments. This system is used for medium-hard blocks; it is also the method of choice for cutting irregularly shaped blocks. The second, most commonly used system employs a multi-blade bandsaw, in which the granite is cut with bands, in this case sheets of carbonised steel. Metal filings are used as the abrasive element that is displaced towards the cutting planes by the movement of the bands. When using metal filings, calcium hydroxide is usually added to avoid the appearance of iron oxide stains on the stone. Processing of the granite into the final elaborated product involves cutting and polishing the slabs to the specified sizes and surface finish. This is carried out with special machines that often incorporate diamond-edged discs and that do not usually require other types of abrasives or additives.

Granite slurries are produced as a by-product of these processes and are formed by water, rock particles, remains of calcium hydroxide and other additives included in the abrasive mixture. The slurry is collected in a deposit from which it is pumped into settlement tanks. The thick slurry is then transported to storage ponds where it is air dried. Although the dry material, that is to say, the powder, is not legally classified as a hazardous waste, its dispersal by wind or water would cause unwanted environmental effects and this is one of the reasons for the great interest in its reutilization.

The underlying hypothesis of the present study is that granite powders can be used to correct the acidity of different materials (soils, mining residues), while at the same time acting as a source of plant nutrients. This use for granite powder is of special relevance in Galicia, where acid soils with a low nutrient status predominate and where agricultural soils are routinely limed to maintain the pH within a range suitable for growing crops (Guitián and Muñoz, 1960; Muñoz and Guitián, 1962).

Furthermore, in Galicia there exist large extensions of mine soils affected by acidity as a result of sulphide oxidation; these may be associated with lignite deposits (Leirós et al., 1995; Monterroso and Macías, 1998) or originate from the exploitation of pyritic materials and other metal sulphides (Calvo and Pérez, 1994). Restoration of the mine soils and dumps usually requires the addition of materials to correct the acidity.

Granite powder may constitute an effective alternative to traditional liming materials for use in correcting the pH of agricultural and forest soils, as well as in restoring mine soils, by combining its amendment capacity with the potential capacity to act as a source of nutrients. Previous studies (Gillman, 1980; Leonardos et al., 1987; Sanz-Scovino and Rowell, 1988; Chesworth et al., 1989; Coroneos et al., 1996; Hinsinger et al., 1996) have provided evidence that crushed rocks may provide a source of nutrient elements that are released to the soil. The aim of the present study is to investigate the physicochemical characteristics of the granite powder produced in the region and to assess its capacity to neutralize acids and to supply nutrients in the short and medium term.

2. Material and methods

The granite powders generated by cutting with both systems described: diamond-edged disc saw (GPM1, GPM2, GPM3, GPM4 and GPM5) and bandsaw (GNT1, GNT2, GNT3, GNT4 and GNT5) were analyzed. The samples were collected from two granite industries in Porriño (province of Pontevedra, Galicia, Spain). The industries in this area mainly use local adamellitic granites, with quartz, abundant biotite and equivalent proportions of potassium feldspar and plagioclase, as well as granodiorites and biotite-amphibole granites, with less potassium feldspar than plagioclase, with biotite as the principal mica (IGME, 1981). The materials being processed were relatively homogenous and therefore the powders were expected to have similar characteristics; however samples were taken during five consecutive days to examine any variability in the powders derived from different stages of the manufacturing processes.

The powder samples were air dried and sieved using a 2 mm mesh sieve; the fraction retained on the mesh was negligible. The general analyses were carried out according to the methods described by Guitián and Carballas (1976). The pH was measured in H₂O and in 0.1 M KCl (1:2.5 powder:solution ratio), and the electrical conductivity (at 25 °C) in an aqueous extract of powder (1:1). Textural analysis was carried out by the international method, quantifying the sand (>50 µm), silt (2–50 µm) and clay (<2 µm) fractions. The mineralogical compositions of the total ground sample and of the clay fraction were determined by X-ray diffraction (Siemens D500 diffractometer with Cu filament). To determine the total content of those constituents of the powder that were expected to have a pH buffering effect, the ground samples ($<50 \mu$ m) were digested with HNO₃, HF and H₃BO₃ in pressure digesters at 120 °C. In the extracts Ca, Mg, Fe and Al were measured by flame atomic absorption spectrometry, and Na and K by emission spectrometry (Varian SpectraAA 220FS).

To assess the neutralizing capacity of the granite powders and to determine the buffering mechanisms acting at different pH intervals, two types of experiments were carried out. On the one hand neutralization curves were determined for suspensions of powder:deionized water (0.5 g in 50 ml) by the addition of 0.1 M HCl to pH 3 using an automatic titrator (Metrohm 702 Titrino). Once the neutralization experiment was concluded, the suspensions were centrifuged and filtered (0.45 μ m), and the concentrations of Na, K, Ca, Mg, Si, Fe and Al in the filtrate were determined as described above.

The neutralizing capacity of the powders and their medium-term capacity to supply nutrients were assessed in a neutralizing experiment at different equilibrium times (1, 7, 15 and 30 d) with the aim of determining the effect of contact time on the buffering effect and the dissolution of the constituents of the powder. The experiment was carried out on samples of the two types of powder (GNT1 and GPM1) and consisted of the addition of increasing quantities of 0.1 N HCl to five suspensions of 1 g of powder in distilled water. The quantities of HCl added to each kind of powder were decided from its neutralizing capacity obtained from the rapid neutralization curves (0-2.40 meq HCl for GNT samples and 0-0.48 meq HCl for GPM samples) with the aim of covering a pH range from 9 to 3. The final density of all suspensions was 0.02 g cm^{-3} (1 g in 50 ml). At the end of the incubation the pH of each suspension was measured and, after centrifugation and filtering $(0.45 \,\mu\text{m})$, the concentrations of Ca, Mg, Si, Fe and Al in the filtrate were determined by flame atomic absorption spectrometry and those of Na and K by emission spectrometry.

3. Results

3.1. General characteristics of the powders

The texture of the powders is loamy-silt, with the fine silt fraction (2–20 μ m) representing more than 50% of all samples. The electrical conductivity was low, between 114 and 570 μ S cm⁻¹, being higher and more variable in the GNT samples. The values indicated a low concentration of soluble salts. The reaction of the powders was alkaline (pH_{H2O} > 9), with small differences among the powders sampled in different days, although, in general, the GPM samples were more alkaline than the GNT ones (Table 1). The pH values in KCl were similar to

those measured in water. This finding is attributable to a low cation exchange capacity of the powders, about $18 \text{ cmol}_{c} \text{ kg}^{-1}$ (Vázquez, 2000), and to the predominance of basic cations in its exchange complex. The fact that the pH of the powders generated by cutting with the diamond-edged saw (GPM) was higher than that of those generated by the bandsaw (GNT), which may include calcium hydroxide, appears to indicate that the high pH values were mainly attributable to the composition of the powders and not to the additives. Given that the granite powder is produced from the abrasion and crushing of the rock during cutting and polishing, we can assume that the value obtained for the pH_{H_2O} will be similar to the abrasion pH, defined as the pH of a suspension of the finely ground material in distilled water. The abrasion pH is related on one hand, to the chemical and mineralogical composition of the material, and on the other, to the physicochemical behaviour of the new surfaces created during the grinding process. The abrasion pH of rocks is usually alkaline because grinding produces an increase in the surface area that favours the dissolution of cations from mineral crystalline networks. The high pH values of the powder samples reflect the predominance of unweathered primary minerals, as confirmed by mineralogical analysis, which indicates that the mineral constituents of the powders are the main components of the granites from which they are produced, with a predominance of feldspars and slightly lower amounts of quartz and micas. Secondary minerals produced by weathering of the rock were not even observed in the $<2 \,\mu m$ fraction (Table 1).

As regards the chemical composition of the powders, the concentrations of Na, K, Mg and Al were very similar in the powders generated by both cutting methods; by contrast, Ca and Fe were more abundant in the GNT powder samples than in the GPM samples as a result of the addition of calcium hydroxide and metal filings during bandsaw cutting (Table 2). The analysis of samples collected on different days showed the texture, pH, mineralogy and major element content of the powders to be similar.

3.2. Neutralization experiments

The variation in pH of the powder samples in suspension on progressive addition of 0.1 N HCl to a final pH of 3.0, within a time of 2–3 h, is shown in Fig. 1. In the GPM samples, the pH decreased rapidly as the acid was added, reaching a final value of pH 3 after addition of between 0.10 and 0.15 cmol H⁺ kg⁻¹. In the GNT samples, however, the variation in pH was more gradual and larger amounts of acid were required to reach a final pH of 3, which indicates the higher buffering capacity of these powders. The acid neutralizing capacity (ANC) to pH 3 (ANC₃), here defined as the quantity of H⁺ required for the suspensions to reach this pH, of the

Table 1			
pH, conductivity (μ S cm ⁻¹)	, particle size distribution	and mineralogy of th	e granite powders

Sample	pН		pH	H EC (μ S cm ⁻¹)		Particle s	Particle size (%)				Clay fraction mineralogy ^a		
	H ₂ O	KCl		<2 µm	2–20 µm	20–50 µm	>50 µm	% Q	% F	% M			
GNT1	9.07	8.84	194	16.5	49.9	28.6	4.5	++	++++	++			
GNT2	9.51	9.72	156	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.			
GNT3	9.66	9.74	416	17.7	54.1	21.4	6.8	++	++++	+			
GNT4	9.62	9.77	570	17.8	51.9	24.1	6.2	++	++++	++			
GNT5	9.54	9.63	356	18.3	51.9	24.0	5.7	++	++++	++			
GPM1	9.52	9.49	148	16.6	56.6	25.9	0.9	++	++++	++			
GPM2	9.74	9.30	114	14.8	52.8	26.6	5.8	++	++++	++			
GPM3	9.55	9.14	114	15.9	55.2	27.2	1.7	++	+++	+++			
GPM4	9.71	9.37	117	14.9	54.5	29.1	1.5	++	+++	++			
GPM5	9.76	9.41	158	15.9	56.2	26.4	1.5	++	++++	++			

n.d.: not determined.

^a Mineralogical composition: Q = quartz; F = feldspars; M = mica (mainly biotite). Abundance: ++++: >50%; ++: 30-50%; ++: 10-30%; +: 3-10%; tr: "<" 3%.

 Table 2

 Concentration of major elements (%) in the granite powders

Concentration of major elements (70) in the grante powders											
Sample	Na ₂ O	K ₂ O	CaO	MgO	Al ₂ O ₃	Fe ₂ O ₃					
GNT1	2.7	4.2	5.4	0.6	14.8	11.0					
GNT2	2.7	4.3	3.8	1.6	12.9	9.3					
GNT3	2.1	2.6	3.4	2.3	11.3	9.4					
GNT4	3.0	4.5	4.0	1.3	22.6	5.4					
GNT5	2.7	4.3	4.9	1.6	21.3	9.0					
$x \pm s.d.^{a}$	2.6 ± 0.3	4.0 ± 0.8	4.3 ± 0.9	1.5 ± 0.6	16.6 ± 5.1	8.8 ± 2.1					
GPM1	2.7	5.2	1.9	0.9	14.1	2.9					
GPM2	2.8	4.1	2.9	1.3	17.8	3.0					
GPM3	2.7	4.8	2.1	0.9	17.8	3.3					
GPM4	2.5	3.9	3.5	1.8	12.7	3.1					
GPM5	2.9	4.5	1.7	0.8	14.5	2.7					
$x \pm s.d.^{a}$	2.7 ± 0.1	4.5 ± 0.5	2.4 ± 0.8	1.1 ± 0.4	15.4 ± 2.3	3.0 ± 0.22					

^a x = mean value; s.d. = standard deviation.

GPM samples varied between 20 and 30 cmol H⁺ kg⁻¹ of powder, whereas that of the GNT samples ranged from 34 to 94 cmol H⁺ kg⁻¹ powder. The ANC was also determined to pH 4.5 (ANC_{4.5}), in order to assess the buffering capacity of the powders without the dissolution of significant amounts of Fe and Al. The values of ANC to pH 4.5 varied between 5 and 11.6 cmol H⁺ kg⁻¹ powder for the GPM samples and between 24 and 61 cmol H⁺ kg⁻¹ for the GNT samples (Table 3).

In the solutions obtained at the end of the experiments, the levels of dissolved Na, K and Mg were slightly higher in the GNT samples, whereas in the GPM samples there was a larger amount of dissolved Al (Table 4). However, the main difference between the two types of powder was the large amount of dissolved Ca in the GNT samples, which can be attributed to the calcium hydroxide added during the manufacturing. If the amount of dissolved element is expressed on the basis of its total content in the powder, it can be observed that only a small proportion is dissolved in the rapid neutralization experiments, with little difference between the GPM and GNT powders. The most soluble elements were Ca and Mg, reaching values of up to 24.5% of the total CaO and 18.9% of the total MgO. The least soluble elements under the experimental conditions were Si, Al and Fe, with less than 0.5% of the total content of the powder (Table 4).

The analysis of the correlation between the ANC₃ value and the amounts of elements dissolved, considering all of the samples, revealed the coefficient corresponding to Ca to be highest (r = 0.68, P < 0.01), similar to that for Mg (r = 0.60, P < 0.01) and higher than that for Na (r = 0.55, P < 0.1).



Fig. 1. Short-term neutralization curves of granite powder GPM and GNT.

Table 3 Acid neutralizing capacity (ANC cmol $H^{+}\,kg^{-1}$ powder) to pH 4.5 (ANC_{4.5}) and pH 3 (ANC_{3})

	Sample										
	GPM1	GPM2	GPM3	GPM4	GPM5	GNT1	GNT2	GNT3	GNT4	GNT5	
ANC _{4.5}	11.6	5	7.4	6.4	8.4	48	61	36	24	41	
ANC ₃	30.0	22	26	22	20	62	94	54	34	67	

The results of the neutralization experiments at increasing contact times (1, 7, 15 and 30 d) carried out with samples GPM1 and GNT1 are shown in Fig. 2. Both powders showed a higher buffering capacity than that obtained in the rapid neutralization experiment, in which the addition of acid was completed within 2-3 h, although there was little difference between the neutralization curves of 1 and 30 d. The buffering capacity of GNT1 was much higher than that

of GPM1. The final pH value of GNT1 tended to stabilize at around pH 5.0, whereas in GPM1 it decreased until pH 3, in spite of being added 5 times more HCl to the former. The values of the ANC_{4.5} were 200 cmol H⁺ kg⁻¹ powder for GNT1, and 27.5 cmol H⁺ kg⁻¹ powder for GPM1, which corresponds to a calcium carbonate equivalent (CCE) of 10.8 and 1.8, respectively (in relation to a value of 100 for pure CO₃Ca).

	*		· /				· · · ·
Sample	Na ₂ O	K ₂ O	CaO	MgO	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂
GNT1	573	416	8540	390	n.d.	109	375
GNT2	674	578	6020	1935	118	191	332
GNT3	640	813	8330	1860	194	431	396
GNT4	674	569	4410	1386	n.d.	<14	257
GNT5	674	455	2730	2310	n.d.	<14	129
$\%$ of total component $^{\rm a}$	2.5	1.6	7.8	10.5	n.d0.17	n.d0.46	0.06
GPM1	287	371	1310	1700	663	198	749
GPM2	505	431	1820	571	314	166	171
GPM3	573	569	1337	375	405	156	118
GPM4	573	446	1330	783	145	<14	150
GPM5	472	455	910.0	50	212	<14	214
% of total component ^a	1.8	1.0	5.8	7.6	0.23	n.d0.68	0.05

Concentration of elements expressed as oxide (mg kg⁻¹ powder) solubilized in the short-term neutralization experiments (final pH = 3)

n.d. = not detected by A.A.S.

^a Mean value of percentage of solubilized element in relation to total element in samples GNT and GPM, respectively; for Al_2O_3 and Fe_2O_3 , minimum and maximum values are reported.

At the end of the experiment the concentrations of Na, K, Ca, Mg, Fe, Si and Al in solution were measured (Tables 5 and 6). In the GNT samples, the main element in solution was Ca (with more than 80% of the total CaO being dissolved), followed by Na and K. Higher concentrations of Fe (up to 24% of the total Fe₂O₃) were detected in solutions of pH < 5, contrasting with the concentrations below the detection limit in those solutions with pH > 5 (Table 5).

In the GPM samples, the main elements were Ca and Mg, followed by Na and K. However, with reference to the total contents, Mg was the most soluble element, reaching a maximum value of 31% of the total MgO, which can be attributed to the dissolution of biotites. The effect of acidification in increasing the solubility of Fe and Al was also evident in the GPM samples (Table 6).

The most notable difference between the two powders was in the amount of dissolved Ca and Fe, which was clearly higher in the GNT samples and may explain its higher ANC. The main source of these elements is the calcium hydroxide and the metal filings added during the cutting process.

The different contact times had little effect on the solubility of the powder components, within the time interval studied (1–30 d), as there was only a slight increase in the amount of dissolved Ca and Na in the GNT samples, on comparing solutions of pH \approx 9.5 after 1 and 15 d. In the GPM samples the main difference was in the concentration of dissolved Mg, which increased between days 1 and 15, then decreased again after 30 d, comparing solutions of pH \approx 8.5.

However, the solubility of the powder components was clearly affected by the pH of the suspension. The

concentration of dissolved cations showed a gradual increase as pH decreases, particularly at pH < 4 with the GPM samples (Table 6). In the GNT samples there was a sharp increase in base cations at around pH 8, coinciding with a marked trend for the pH of these samples to remain close to this value (Table 5). This indicates the action of a buffering system that maintains the pH of the samples within this range, and that corresponds to the dissolution of calcium carbonate, originated from the carbonation of the calcium hydroxide added during the cutting process. In both kinds of powders, the solubility of Al and Fe increased sharply at pH below 5. Likewise, Si was slightly more soluble at low pH values, probably as a consequence of a more intense hydrolysis of silicates.

4. Discussion and conclusions

The initial hypothesis of the present study was that granite powders could be used as amendments to correct soil acidity. Soil acidity represents a serious problem in the region where the powders under study are produced, due to the predominance of siliceous substrates on which soils of sandy texture, acid pH (often below 4.5), with low base saturation develop, and where liming of agricultural soils is routinely carried out.

The results indicate that the granite powders may be effective correctors of acidity, as they are alkaline (pH > 9) and demonstrate a certain ANC. Both properties are attributable to the rapid release of basic cations (Ca, Mg, Na and K) exposed on the surface of silicates; the grinding process that the powder undergoes considerably increases the surface area,

Table 4



Fig. 2. Medium-term neutralization curves for GPM1 and GNT1s (1 d to 30 d) in comparison with the short-term experiment (2-3 h).

favouring its dissolution. In the particular case of the bandsaw-generated powder (GNT), the additives incorporated during the cutting process (calcium hydroxide and iron filings) provide an additional neutralizing capacity.

The powders therefore combine an acid correcting capacity with the potential to provide elements essential to plants, such as Ca and Mg (which are scarce in the soils of the region), as well as K. Several authors have proposed the use of crushed rock as a slow release fertilizer in highly weathered soils and leached environments, where very soluble fertilizers may be lost through leaching (Gillman, 1980; Leonardos et al., 1987; Sanz-Scovino and Rowell, 1988; Chesworth et al., 1989; Weerasuriya et al., 1993; Coroneos et al., 1996; Hinsinger et al., 1996).

One important aspect of the capacity of rock powders to provide nutrients is their texture (Harley and Gilkes, 2000). A fine granulometry favours the dissolution of minerals on presenting a larger surface area in contact with the solution. The granite powders analyzed in the present study present a fine texture, dominated by the $2-20 \mu m$ fraction, which is very favourable in terms of potential release of nutrients.

Previous studies on the use of crushed rock in general, and of granite powders in particular, have basically addressed the transfer of potassium, and they have provided contradictory results. Bakken et al. (2000) observed that the K in potassium feldspar was not available and the K in biotite was only released very slowly, concluding that granite powders were not very effective as potassium fertilizers. Similarly, Bolland and Baker (2000) concluded that granite powder was not an effective fertilizer. In contrast, Weerasuriya et al. (1993) assessed the capacity of acidulated pegmatitic mica to release nutrients and found that an acid treatment increased the solubility of all kinds of rock powders, with the materials richest in biotite being those with the greatest potential for supplying nutrients. The results of the present study show that the element Table 5 Concentration of elements expressed as oxide (mg kg⁻¹ powder) solubilized in medium-term neutralization experiments of sample GNT

	pН	Na ₂ O	K ₂ O	CaO	MgO	Al_2O_3	Fe ₂ O ₃	SiO ₂
GNT 1 d	9.58	708	376	606	71	<104	24.3	342
	8.35	792	541	6090	249	<104	<7	235
	7.83	879	629	11130	280	<104	<7	235
	7.27	876	667	21420	404	n.d.	<7	310
	6.07	1129	910	40390	601	<104	3939	274
	5.45	1129	955	42210	738	291	31 286	273
GNT 7 d	9.07	674	358	1680	124	<104	11	396
	8.10	876	563	6125	253	<104	<7	<225
	7.94	994	682	11165	253	<104	<7	235
	7.50	1129	782	22610	415	<104	<7	326
	5.47	1112	1057	39410	647	<104	2143	353
	4.83	1297	1129	42350	740	571	23 0 3 5	299
GNT 15 d	9.54	1011	401	1470	116	<104	<7	235
	8.15	1011	691	6405	278	<104	<7	<225
	8.00	1011	774	11130	336	<104	<7	<225
	7.77	1061	840	21770	4201	<104	<7	241
	5.38	1179	1057	42088	688	198	1328	428
	4.55	1432	1153	44975	775	741	22321	385
GNT 30 d	8.77	775	464	1159	135	<104	<7.1	353
	8.07	960	696	7000	230	<104	22	278
	7.97	1011	712	10185	251	<104	24	<225
	7.79	1112	846	23625	431	<104	26	251
	5.16	1247	1057	43225	674	180	1064	535
	4.27	1385	1185	42175	763	987	27 000	1037
Max. % ^a		5.3	2.8	83.3	12.9	0.7	28.4	0.22
Min. % ^a		2.5	0.9	1.1	1.2	_	-	_

-: Under the detection limit.

^a Maximum and minimum values (%) of solubilized element in relation to total concentration of the element in sample GNT1. Maximum values usually correspond to lower pH values in the suspensions while minimum values correspond to higher pH values.

released in greater quantities as a consequence of the addition of acids is not K, but rather, Ca and Mg. The release of these elements occurs during the first hours of contact with acid solution, without a significant increase in solubility after longer contact times. This appears to indicate that these elements are retained with little energy on the mineral surfaces and that significant dissolution of the siliceous networks does not occur, a finding that is corroborated by the low concentrations of silica in the solutions. These experiments were carried out without renewal of acid solutions, therefore it is expected that in open system—as in most soils of Galicia—in which there is constant renewal of attacking solutions, the efficacy of cation release will be even greater.

One question that should be taken into account is the heavy metal content of the powders (Table 7), which is usually higher in the bandsaw-generated powders than in the diamond-edged disc saw slurries, particularly the contents of Mn, Cr and Ni, elements that are associated with the iron in the metal filings added (Vázquez, 2000). Some of these metals are micro-nutrients required by plants and, therefore, their presence in the powders is beneficial, as long as the concentrations do not reach toxic levels. The dissolution of heavy metals usually increases with decreasing pH. Moreover, in the case of the GNT powders, which contain metal filings, the solubility of heavy metals increases with the increase of the solubility of the iron with which they are associated. Theoretically, the dissolution of iron would be significant only below pH 3 under oxidizing conditions; however, in this case, the dissolution of iron begins to be significant below pH 5. The risk of heavy metals release would be of concern particularly when attempting to correct the acidity of mine soils, which can be very acidic. In this case, the use of bandsaw-generated powders would have to be avoided or the procedures to recapture the metal shot improved, in order to reduce the incorporation of metals into the powders.

Therefore, for optimum use of the powders, combining its liming effect with maximum use of the nutrients,

Table 6					
Concentration of elements (mg kg ⁻¹	powder) solubilized	in medium-term	neutralization e	experiments of s	sample GPM

	pН	Na ₂ O	K ₂ O	CaO	MgO	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂
GPM 1 d	9.08	505	340	554	493	<104	<7	193
OT M T U	8.23	629	461	879	1187	<104	<7	278
	7.44	640	525	1087	1157	<104	16	342
	5.39	725	682	1425	1777	<104	25	235
	3.44	876	1077	2197	2579	1365	720	353
	2.79	809	1214	3273	2649	2514	807	257
GPM 7 d	8.34	505	358	712	657	n.d.	7	460
	8.00	657	447	814	661	<104	<7	294
	7.59	724	513	877	910	<104	<7	321
	5.56	674	798	1213	1977	n.d.	11	283
	3.71	910	1171	2323	2540	1140	521	497
	3.08	1095	1348	2884	2774	2588	1245	823
GPM 15 d	8.21	607	434	869	896	<104	<7	513
	7.96	674	471	878	717	<104	<7	364
	7.60	792	495	1136	1070	<104	<7	337
	5.82	893	857	1334	1811	<104	<7	444
	3.96	1095	1281	2565	2384	1119	170	460
	3.25	11456	1565	2886	2769	2748	1245	652
GPM 30 d	8.23	741	419	934	493	<104	27	439
	8.06	876	486	805	6780	<104	26	380
	7.65	859	533	1034	1080	<104	28	401
	5.68	977	849	1389	1855	<104	29	192
	3.96	943	1265	2249	2500	10158	764	738
	3.62	1079	1594	2879	2717	1894	1221	936
Max. % ^a		4.2	3.0	17.2	30.8	1.8	4.3	0.15
Min. % ^a		1.9	0.6	2.9	5.5	_	-	0.03

-: Under the detection limit.

^a Maximum and minimum values (%) of solubilized element in relation to total concentration of the element in sample GPM1. Maximum values usually correspond to lower pH values in the suspensions while minimum values correspond to higher pH values.

Table 7 Mean values of total heavy metal concentration (mg kg^{-1}) in the granite powders studied

	•			*		
	Cr	Cu	Mn	Ni	Pb	Zn
GNT $x \pm s.d.^{a}$	156 ± 44	83.7 ± 28.7	908.2 ± 180	51.4 ± 8.1	37.4 ± 66.9	63.3 ± 4.9
$GPM \\ x \pm s.d.^{a}$	33 ± 6.4	56.5 ± 7.2	386 ± 43.8	28.5 ± 12.5	32.3 ± 2.8	70.7 ± 10.5

^a x = mean value of the five GNT sample and the five GPM samples, respectively; s.d. = standard deviation.

while minimizing the risk of dissolving heavy metals at toxic levels, the powder should be applied at doses that allow the pH of the soil to reach approximately pH 6, which is moreover the most suitable pH for many crops.

Although the liming effect of the granite powders is lower than that of other common liming materials, which implies the use of higher doses, this should not be a drawback as the powder is a waste product that at the moment has no other use and is therefore available free of charge at the source of origin. Addition of large quantities of the material may have other benefits due to a certain improvement in soil texture when applied to sandy soils.

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