Evaluation for the Potential Use of Silicate Rocks from Four Volcanoes in Indonesia as Fertilizer and Soil Ameliorant

Joko Priyono, Raden Sutriono, and Zaenal Arifin[1]

Received 10 January 2007 / accepted 11 August 2008

ABSTRACT

Evaluation for the Potential Use of Silicate Rocks from FourVolcanoes in Indonesia as Fertilizer and Soil Ameliorant (J. Priyono, R. Sutriono, and Z. Arifin): Silicate rocks, the abundant plant nutrient source in Indonesia, have not been evaluated for use as a fertilizer/and soil ameliorant. This research was aimed to identify (1) mineral and elemental compositions of silicate rocks originated from Galunggung, Kelud, Tambora, and Rinjani Volcanoes and (2) soil properties determining dissolution rate of plant nutrients from the silicate rock fertilizers (SRFs). The rocks were ground with a ball mill for 10 min providing SRFs with medians of particle size of 30 – 50 μm. Each SRF was added to 6 soils from West Java, East Java, and Lombok Island at a rate equivalent to 20 t ha-1, incubated for 28 days in a laboratory condition. Results indicate that adding SRFs clearly increased soil pH with negligible effect on soil salinity. Adding SRFs also increased quantity of citric-oxalic-extractable plant nutrients (Ca, K, Zn, and Cu) and activity of soil micro-organisms. Dissolution of plant nutrients from the SRFs in the soils was mainly determined by combination factors of C-organic content and pH of soils before application of the SRFs. It was concluded that SRFs originated from those volcanoes may be used as a plant-multi nutrient source and a remedial agent for acidic and biologically degraded soils. However, the true effectiveness of SRFs for those uses needs to be further tested under various soil-plant systems.

Keywords: Ameliorant, basaltic, plant nutrients, silicate rock fertilizers, volcanic rocks

INTRODUCTION

During the last two decades, the possibility of using silicate rocks as fertilizers has received significant attention from agronomists and soil scientists, and some advantages over chemical fertilizers have been proposed by many researchers, such as Leonardos *et al*. (1987 and 2000), Coroneos *et al*. (1996), Hinsinger *et al*. (1996), Bolland and Baker (2000), Coventry *et al*. (2001), and Priyono (2005). In Indonesia, various silicate rocks are abundant, originated from about 130 active volcanoes. However, evaluation for the potential use of the materials as a plant-nutrient source/and soil ameliorant never been done.

For many developing countries, including Indonesia that spends scarce dollars to import chemical fertilizers, locally produced silicate rock fertilizers (SRFs) may be an appropriate material for their farming systems. From an environmental point of view, applying SRF is non-polluting due to the slow release of nutrients to soil solution such that water pollution resulting from leaching or erosion of SRF from agricultural land will be least. Furthermore, SRF does not contain elevated levels of contaminants such as Cd, F, and U that occur in some chemical fertilizers and thus provide a more sustainable source of plant nutrients. The use of SRFs in broad scale agriculture has also been proposed for the utilization of quarry by-products in Western Australia (Coroneos *et al*., 1996; Hinsinger *et al*., 1996; Bolland and Baker, 2000), Queensland (Coventry *et al*., 2001), and Brazil (Leonardos *et al*., 1987), and the utilization of mine tailing (Bakken *et al*., 1997 and 200). Quarry industries have been operated in many places in Indonesia, mainly producing coarse-rock materials used for building and other constructions. But, no attempt has been made to use the materials for

[1] Department of Soil Science, University of Mataram Jln. Pendidikan 37 Mataram, Lombok Island, NTB, Indonesia
Corresponding author: Joko Priyono, Phone/Fax: +62 370 644793/+62 370 628143;
e-mail: jokotanahunram@gmail.com

J. Tanah Trop., Vol. 14, No. 1, 2009: 1-8
ISSN 0852-257X

agricultural purposes. The rocks are most likely to be suitable fertilizers and soil ameliorant for farming systems in this country.

This paper presents results of the first part of a multi year research relating to the evaluation for the possible use of silicate rocks, or in combination with organic materials and bio-fertilizer, as effective and environmentally sound fertilizer and soil ameliorant. The objectives of this research were to identify (1) the properties of silicate rocks originated from four volcanoes in Indonesia, associated to their potential use as fertilizer/and soil ameliorant and (2) soil properties determining dissolution rate of plant nutrients from the SRFs in soil.

MATERIALS AND METHODS

Rock and Soil Samples

Silicate rocks were collected from the slope of Mt. Galunggung (in West Java), Mt. Kelud (in East Java), Mt. Rinjani in Lombok Island (which has been processed by a quarry industry in Mataram for road construction), and Mt. Tambora (in Sumbawa Island). The bulk samples of rocks were washed with water, air dried, and broken with a hammer to about 0.5-cm diameter. A 2kg of broken rock was ground for 10 minutes with a ball mill having capacity of 11.3L using 5 kg of ∅ 22mm-stainless steel balls. This milling time was presumed to be the optimum milling time based on result of Priyono (2005). Sub samples of ground rocks, termed as SRFs, were taken for mineralogical and total elemental analyses. The mineral composition of the SRFs was interpreted from their x-ray diffraction (XRD) patterns which were collected by using a Phillip Analytical X-ray B.V. with a PW1710 diffractometer using monochromatized Cu-Kα (λ = 1.54056 Å), generated at 40 kV and 30 mA. The diffraction intensity was recorded between 5 and 70° 2θ at a scanning rate of 0.02° per second. The XRD patterns of the ground rocks were presented in Figure 1.

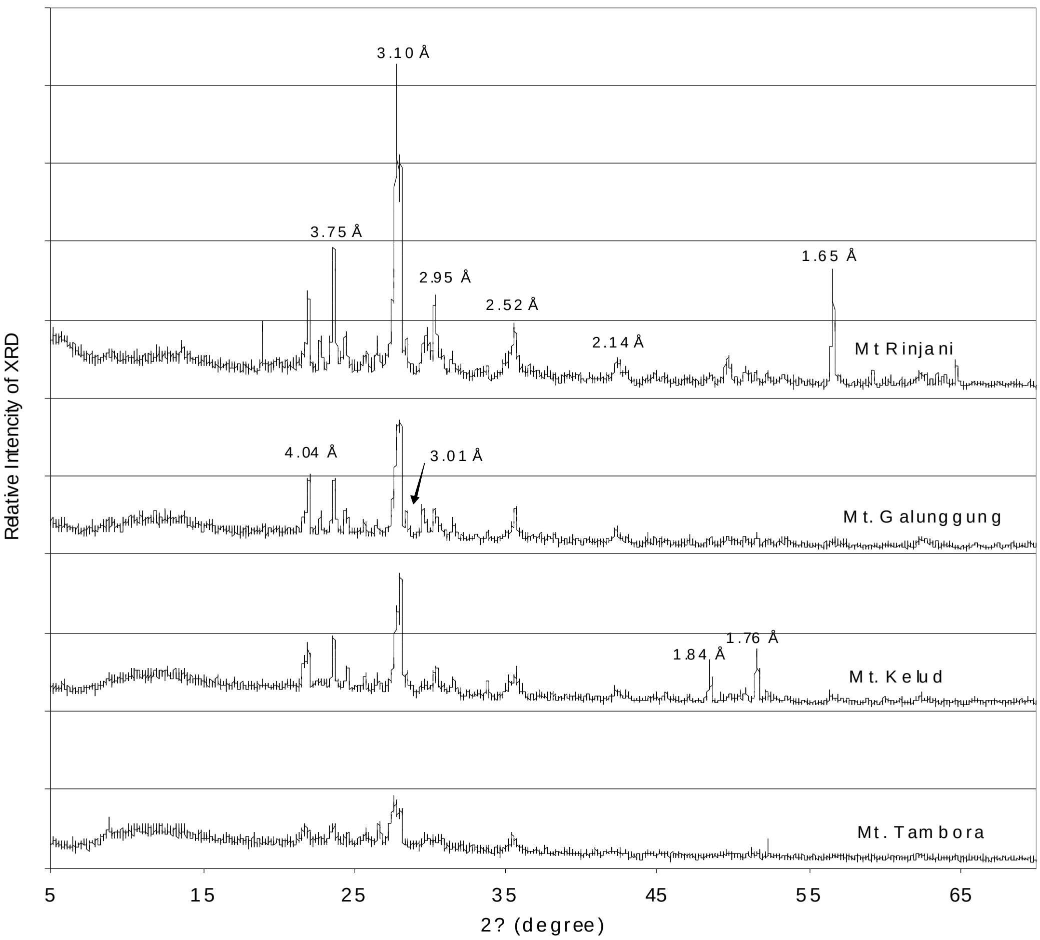

Figure 1. XRD patterns of the 10 min-ball milled rocks originated from Rinjani, Galunggung, Kelud, and Tambora volcanoes with d-spacing of several peaks

Total elements composing the SRFs were identified using a wet digestion method with HF and H_3BO4 (modified Jackson, 1958). Results of this analysis are presented in Table 1. Distribution of particle size was identified by using a pipette method (Gee and Bauder, 1986 with some modifications for sampling time and pipeting depth). Result of this measurement is presented in Figure 2.Soil samples of 20 cm-tops, excluding organic layers, were collected from six different places (from wet to dry areas), i.e., from Jasinga-Bogor, West Java (Oxisol), Darmaga-Bogor, West Java (Ultisol), Lamongan-East Java (Entisol), Batu-Malang, East Java (Inceptisol), Wonosalam-Mojokerto, East Java (Alfisol), and from Kayangan, West Lombok (Inceptisol). The samples were air-dried, lightly ground to break large aggregates, and screened to pass a 2mm-seiver. Soil pH_{H2O} and EC (1 : 5) were measured consecutively

Table 1. Mineral and total elemental (%) composition of SRF.

No.	Element (oxide)	R1 (Tambora)	R2 (Kelud)	R3 (Galunggung)	R4 (Rinjani)
1.	SiO_2	51.78	51.98	54.73	52.28
2.	Al_2O_3	26.23	25.14	24.36	24.77
3.	CaO	7.12	6.95	7.38	4.84
4.	MgO	3.36	3.03	3.30	1.83
5.	K_2O	0.37	1.19	0.55	6.30
6.	Na_2O	2.06	2.19	1.88	3.25
7.	FeO	8.56	8.99	7.25	6.24
8.	MnO	0.16	0.16	0.16	0.15
9.	ZnO	0.01	0.01	0.01	0.01
10.	CuO	0.34	0.36	0.38	0.33
11.	Others	< 0.01	< 0.01	< 0.01	< 0.01
	Total *	100	100	100	100
Mineral composition**		Augite Mg-hornblende Hyperstane Albite Anothite Mica Muscovite	Augite Fe-fargasite Tremolite Albite Anothite Mica Muscovite	Augite Hyperstane Albite Anothite	Gendrite Fargasite Albite Anorthite Muscovite

* Normalized to 100 %

** Ranged to its relative abundance

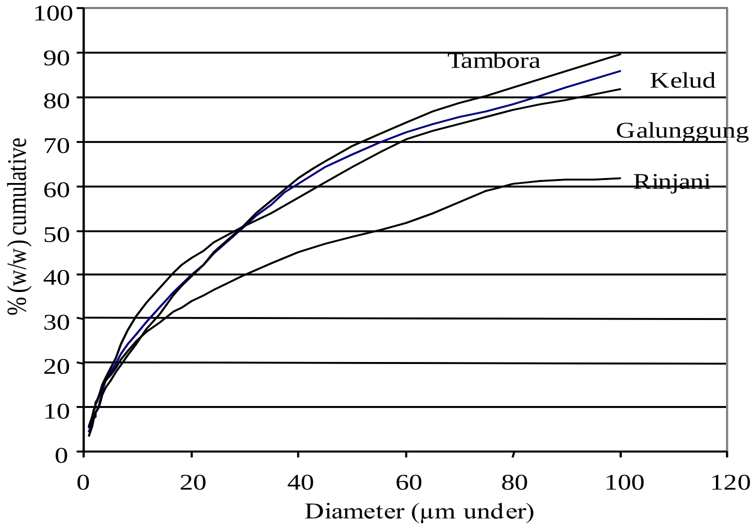

Figure 2. Particle size distribution of SRFs ball milled for 10 minutes.

with pH- and EC- meter; CEC was identified by using 1N NH_4Act pH 7 (Thomas, 1982), C-organic content was determined with the method of Wakley and Black (1934), the contents of exchangeable base cations were measured from the filtrates of CEC measurement using AAS, and soil texture was identified with a pipette method (Gee and Bauder, 1986). The results of soil analysis are presented in Table 2.

Incubation Experiment

A 5 g of SRF and a 250 g of air-dried soil were mixed in a 500mL-plastic bottle, moisten with H_2O to about 125 % of its field capacity, and cupped. Triplicates and a control (soil without SRF) of the mixtures were prepared, then were incubated in laboratory condition at a temperature ambient of 22 – 25^o C. Sub samples of incubated soils were taken after 28 days of incubation period for analyses of pH,EC (using above methods), and quantities of Ca, K, Zn, and Cu extractable in 0.01M citric-oxalic extracting solution. A 5g moist soil + 25mL citric-oxalic solution in a 50mL-plastic tube was shaken on a rotary shaker for 2 hours and the solution was filtered. The concentrations of Ca, K, Zn, and Cu in the filtrates were measured with AAS. The change of soil properties due to application of SRF (e.g., “pH, “EC, “Ca, “K, “Zn, and “Cu) were calculated from the corresponding values for treated soils minus that for the control.

Another set of incubation experiment was prepared in duplicates for observation of soil biological activity, e.g., mixtures of SRF (from Mt. Tambora and Mt. Galunggung) + those 6 soils and controls (soils without SRF). The plastic bottles used for this experiment were facilitated with lines for CO_2 outflow and atmosphere inflow (for supplying O_2 to the soils). The CO_2 produced by soil organism activity during incubation period was cached with 0.1N KOH solution. The total CO_2 was measured weekly up to 3 weeks using a titration method with 0.01 NaOH. The value of “CO_2 was calculated from total CO_2 produced by treated soils minus that for untreated soil (control).

Statistical Methods

Analyses of variant were applied to identify the effects of SRF to each of the changes of dependent variables, i.e., “pH, “EC, “Ca, “K, “Zn, “Cu, and “CO_2. Soil properties that significantly determine the values of these dependent variables were identified using linear-bivariate and multivariate (forward-step wise) analyses. These statistical analyses were done using STATISTICA 6 software.

RERSULTS AND DISCUSSION

General Characteristics of SRF and Soil

As shown in Table 1, the mineral and chemical compositions of the 4 rocks are quite similar, which are dominated by ferromagnesian silicates such as augite, hornblend, and pyroxenes with some feldspars and micas. The rocks contain 51 – 55% SiO_2, so they

Table 2. Several properties of soils used in this experiment.

No.	Soil Properties	Unit	Soil Type*					
			T1	T2	T3	T4	T5	T6
1.	Sand	%	34.43	24.24	51.12	22.24	44.29	80.61
2.	Silt	%	26.29	59.04	27.07	21.34	37.17	13.80
3.	Clay	%	39.28	16.72	21.81	56.42	18.54	5.59
4.	pH_{H2O} (1:5)	-	4.30	4.88	5.40	4.99	7.54	6.53
5.	EC (1:5)	μS.cm^{-}	56.60	48.40	31.10	35.80	59.70	54.60
6.	C-organic	%	0.59	1.68	0.87	1.22	2.77	0.27
7.	CEC	$cmol_c kg^{-1}$	50.58	20.32	26.24	26.40	48.66	5.33
8.	ECEC	$cmol_c kg^{-1}$	27.68	19.57	25.84	25.85	48.41	4.93
9.	Exch. Ca	$cmol_c kg^{-1}$	10.90	4.62	4.62	12.34	43.62	3.11
10.	Exch. Mg	$cmol_c kg^{-1}$	3.56	0.66	2.38	0.39	0.13	0.30
11.	Exch. K	$cmol_c kg^{-1}$	0.41	0.69	0.86	1.41	0.45	0.70
12.	Exch. Na	$cmol_c kg^{-1}$	0.34	0.45	0.28	0.49	0.20	0.34
13.	Exch. Acidity	$cmol_c kg^{-1}$	22.90	0.75	0.40	0.55	0.25	0.40
14.	Base Saturation	%	30.05	31.52	31.01	55.43	91.24	83.57

* T1 = Oxisol – Jasinga; T2 = Ultisol – Darmaga; T3 = Inceptisol – Batu Malang; T4 = Alfisol – Wonosalam; T5 = Entisol – Lamongan; T6 = Inceptisol – Kayangan

may be grouped as basaltic rocks (Deer *et al*., 1992). These types of rocks are dissolved more quickly in most soils than for felsic or silicious rocks (Aubert and Pinta, 1977; Deer *et al*., 1992; Priyono, 2005). Total content of aluminum is 24 – 26% Al_2O_3, calsium and magnesium respectively are 5 – 7% CaO and 2 – 3% MgO. The total content of potassium for rock from Rinjani is much higher (e.g., about 6% K_2O) than that for the other three rocks (0,3 – 1% K_2O). The total contents of other metal elements of the rocks are < 1%, except that for Fe (i.e., 6 – 8% FeO_2). Based on their plant-nutrient composition, these volcanic rocks seem to be appropriate for a multi-nutrient fertilizer.

The properties of soils used in this experiment (Table 2) vary widely. Soil texture or clay content is ranged from coarse (6% clay) to fine (57% clay); soil pH is 4 – 7.5; C-organic content is 0.2 – 1.7 %; and CEC and base saturation (BS) are 5 - 51 $cmol_c$ kg^{-1} and 30 – 91%, respectively. For soil developed from K-rich chalk stones, soil T5 (Entisol-Lamongan), the content of exchangeable Ca is 43.6 $cmol_c$ kg^{-1} which is much higher than that for the other soils.

Effects of SRF on Soil pH and EC

The mean values of “pH and “EC are presented in Figure 3. As shown in the figure, the application of the SRFs at a rate equivalent to 20 t ha^{-1} significantly increased soil pH and EC (“pH and “EC were positive). The increases of pH were from 0.01 to 0.3 units and those for EC were from 1 to 24 µS cm^{-1}.

The positive liming effects of adding SRF into soils were also reported by many other researchers (Holdren and Berner, 1979; Gillman, 1980; Gillman *et al*., 2001 and 2002; Leonardos *et al*., 1987 and 2000; Wang *et al*., 2000; Coventry *et al*., 2001; Harley, 2002; Priyono and Gilkes, 2004), indicating the potential use of SRF as an ameliorating agent for acidic soils. The very low increase of soil EC in this present research indicates the minimum negative effect of SRF application to soil salinity hazard. Similar trends with those results were also shown by Harley (2002) and Priyono (2005).

Quantity of Nutrients Dissolved from SRFs

The mean percentage of plant nutrients (“Ca, “K, “Cu, and “Zn) dissolved from applied SRFs relative to total content of corresponding nutrient in SRF is presented in Figure 4. As shown in the figure, the quantity of most plant nutrients dissolved from SRFs was quite different among soil types. The value of “Ca for soils T5 (Entisol-Lamongan) and T2 (Ultisol – Darmaga) were similar, e.g., about 13 %, but that for the other soils were 2 – 7 fold lower. A note should be made that soil T5 already contained high Ca (e.g., 43.62 $cmol_c$ kg^{-1}, see Table 2), so the addition of Ca from SRFs to this soil practically was meaningless. The highest values of “K, “Zn, and “Cu, were for soil T1 (Oxisol-Jasinga) (e.g., about 25, 20, and 15 %, respectively) which were 2-10 fold larger than those for the other soils. Based on the dissolution of these nutrients, it may be concluded that soil T2 was the most responsive to the application of SRFs.

Results of simple bivariate and multivariate analyses for the quantity of dissolved nutrients from SRFs are summarized in Tables 3 and 4. As shown in Table 3, soil properties individually determined less

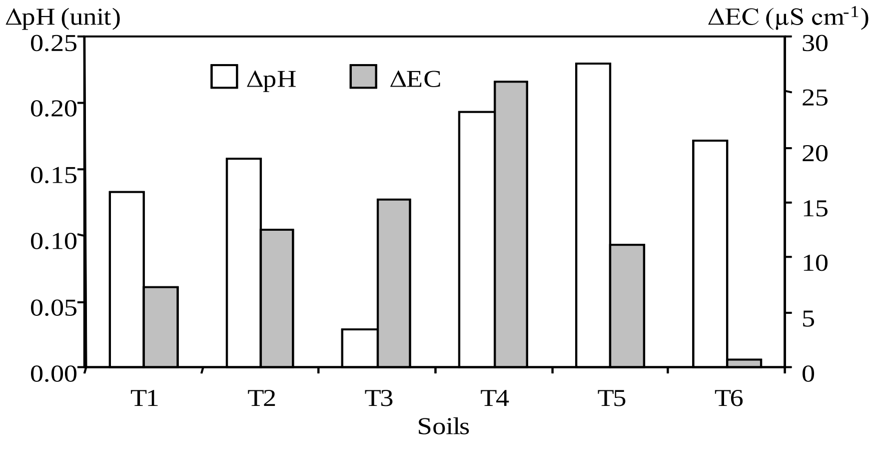

Figure 3. Mean values of —pH and —EC for each type of soil. Notations for soil type (T1 – T6) refer to the explanation in Table 2.

.

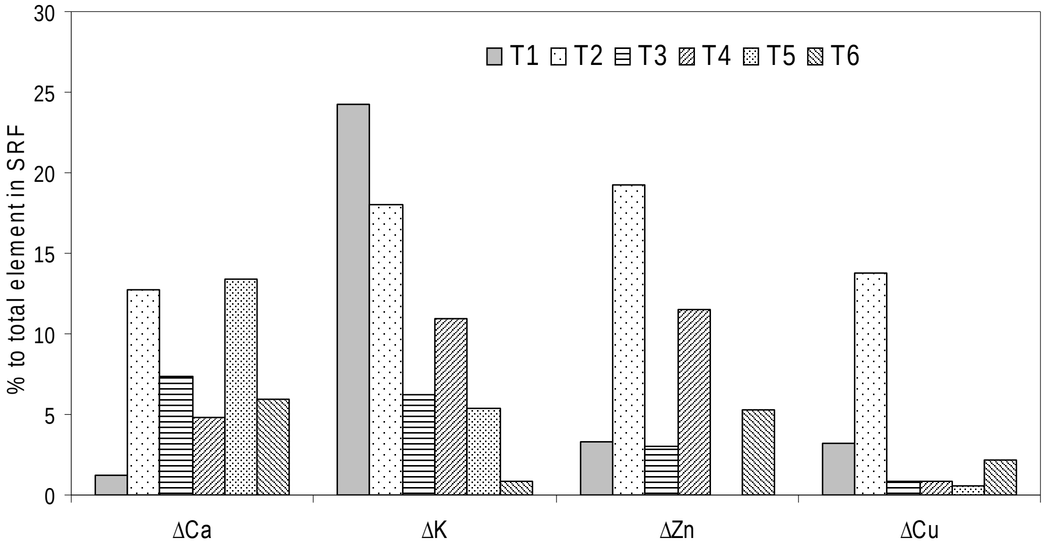

Figure 4. Mean percentage of dissolved nutrients from SRFs (“Ca, “K, “Zn, and “Cu) in each soil (T1 – T6). Notations for soil type refer to the explanation in Table 2.

than 50% to variation of the quantity of nutrients dissolved from SRFs (“Ca, “K, “Zn, and “Cu). However, further analysis (Table 4) indicates that soil C-organic content in association with soil pH (at initial condition) determined about 95% to variation of the values of “pH, “Ca, K, “Zn, and “Cu. Clearly, soil C-organic content together with soil pH were the main determinant factors for dissolution of plant nutrients from SRFs in soils. This finding was much different with that by other researchers. For examples, Hughes and Gilkes (1994) found that clay content in combination with exchangeable acidity of soils contributed only about 48% to the variation of dissolved rock phosphates in soils. Priyono and Gilkes (2004) found larger contribution of those soil properties to the variation of dissolution of ground-silicate rocks in soils from Western Australia (e.g., R^2 was about 60 %). In both experiments, the activity of soil organism in incubated soils was eliminated by adding toluene, while in this present experiment, no biological suppressant was used. Therefore, there was an indication that soil organism activity had significant effects on dissolution of SRF in soil.

Organic acids have important rule in dissolving rocks and minerals (Huang and Keller, 1970; Welch and Ullman, 1996; Blake and Walter, 1999; Zhang and Bloom 1999; Oelkers and Gislason, 2001). The

Table 3. Coefficient determination (R^2) for simple-linier relationship between quantities of nutrient dissolved from SRFs with soil properties.

No.	Soil Properties	Quantity of Nutrient Released from SRFs			
		ΔCa	ΔK	ΔCu	ΔZn
1.	Clay (%)	0.23	0.03	0.09	0.08
2.	Sand (%)	0.00	0.06	0.03	0.04
3.	C-organic (%)	0.36	0.00	0.00	0.00
4.	pH_{H2O} (1:5)	0.28	0.10	0.07	0.08
5.	CEC ($cmol_c.kg^-$)	0.01	0.12	0.07	0.08
6.	ECEC ($cmol_c.kg^-$)	0.05	0.02	0.10	0.11
7.	Base Saturation (%)	0.13	0.13	0.10	0.09
8.	Exch. Ca ($cmol_c.kg^-$)	0.14	0.00	0.11	0.11
9.	Exch. K ($cmol_c.kg^-$)	0.04	0.04	0.03	0.02
10.	Exch. (Al^{+3} + H^+) ($cmol_c.kg^-$)	0.28	0.17	0.00	0.00

Table 4. Equations and coefficient of determination (R^2) for multirelationships between quantities of nutrients released from SRFs with soil properties.

No	Equation	R^2
1.	ΔCa (% total) = - 3.075 + 0.495 (C-org. %) + 0.472 (pH)	0.97
2.	ΔK (% total) = - 4.384 + 0.470 (C-org. %) + 0.475 (pH)	0.97
3.	ΔCu (% total) = - 1.007 + 0.512 (C-org. %) + 0.449 (pH)	0.95
4.	ΔZn (% total) = - 1.730 + 0.508 (C-org. %) + 0.461 (pH)	0.96

acids may act as cation exchangers and chelating agents, especially for polyvalent cations. The involvement of soil organic in determining dissolution of nutrients from SRFs (Table 4) was possibly associable to the function of soil organic as the main source of soil organic acid (John, 1998). The higher soil organic content for soils with high/neutral pH, the more active soil organisms decomposed soil organic matter, so the more organic acids were produced in these soils. In other word, contribution of soil organic was parallel with that for quantity of soil organic acid in determining dissolution rate of nutrients from SRF in soil

Effect of SRFs to Soil Organism Activity

The application of SRFs significantly increased the activity of soil organism, as indicated by increasing respiration rate (positive values of •CO_2, Figure 5). The increase of respiration rate for soils T1, T2, and T3 was about 0.3 cmol kg^{-1}, whereas that for soils T4, T5, and T6 was about 3 fold higher (0.7 – 1.0 cmol kg^{-1}). Results of a simple bivariate analysis for the relationships of •CO_2 with soil properties (Table 2) indicated that the value of •CO_2 was significantly correlated only to soil base saturation (with r = 0.91). Biological reactions in the soil are so complex that available data in the present research are insufficient to provide further explanation. Practically, however, SRFs may be use as soil biological ameliorant.

CONCLUSION

Silicate rocks originated from Galunggung, Kelud, Rinjani, and Tambora volcanoes are potentially appropriate materials for use as a multinutrient fertilizer/and soil ameliorant in general. Application of SRFs (e.g., finely ground silicate rocks originated from those volcanoes) clearly increased soil pH, so those were potentially used as liming materials with negligible effect on soil salinity. The application of the SRFs also increased the quantities of plant nutrients (Ca, K, Zn, and Cu) extractable in 0.01M citric-acetic acids and activity of soil organism. The dissolution of these nutrients from added SRFs in various soils was mainly determined by soil C-

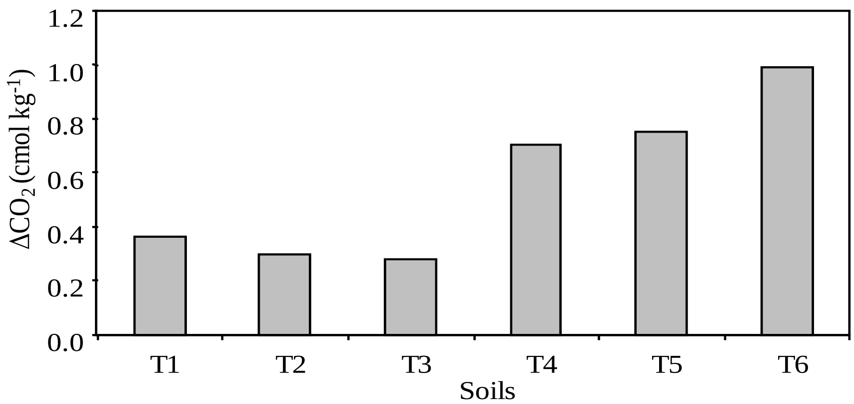

Figure 5. The mean increase of respiration rates (“CO_2) due to application of SRFs, incubated for 28 days. Notations for soil type (T1 – T6) refer to the explanation in Table 2.

organic content in association with soil pH. Practically, SRFs may be used as a plant-nutrient source and soil ameliorant, especially applicable for organic-rich acidic/and biologically degraded soils. However, the true effectiveness of SRFs as fertilizers and soil ameliorant should be tested in soil-plant systems, observed in both short and long terms.

AKNOWLEDGEMENT

We would like to thank to Directorate General of Higher Education (Dirjen Dikti) Republic of Indonesia for its financial funding for this research through the competitive research program (*Hibah Bersaing XIV*). Special thank to Mr. Yopi, a XRD laboratory technician, Department of Mining Geology, ITB, for his helps in mineral analysis.

REFERENCES

Aubert, H. and M. Pinta, 1977. Trace element in soils. Elsevier Sci. Publ. Co., New York.

Blake, R.E. and L.M. Walter. 1999. Kinetics of feldspar and quartz dissolution at 70-80°C and near-neutral pH: effects of organic acids and NaCl. Geochem. Cosmochem. Acta 63**:** 2043-2059.

Bolland, M.D.A. and M.J. Baker. 2000. Powdered granite is not an effective fertilizer for clover and wheat in sandy soils from Western Australia. Nutr. Cycl. Agroecosyst. 56: 59-68.

Coroneos, C., P. Hinsinger, and R.J. Gilkes. 1996. Granite powder as a source of potassium for plants: a glasshouse bioassay comparing two pasture species. Fert. Res. 45: 143-152.

Coventry, R.J., G.P. Gillman, M.E. Burton, D. McSkimming, D.C. Burkett, and N.L.R. Horner. 2001. Rejuvenating soils with Minplus™, a rock dust and soil conditioner to improve the productivity of acidic, highly weathered soils. A Report for RIRDC, Townsville, Qld.

Deer, W.A., Howie, R.A., and Zussman, J. 1992. An introduction to rock-forming minerals. Longmans Scientific & Technical, Essex, UK.

Gee, G.W. and J.W.Bauder. 1986. Particle size analysis. In: A. Klute (Ed.). Methods of soil analysis, Part 1. Physical and mineralogical methods. ASA, SSSA Inc Publ.: Madison, WI. pp. 383-411.

Gillman, G.P. 1980. The effect of crushed basalt scoria on the cation exchange properties of a highly weathered soil. Soil Sci. Soc. Am. J. 44: 465-468.

Gillman, G.P., D.C. Burkett, and R.J. Coventry. 2001. A laboratory study of application of basalt dust to highly weathered soils: effect on soil cation chemistry. Aust. J. Soil Res. 39: 799-811.

Gillman, G.P., Burkett, D.C., and Coventry, R.J., 2002. Amending highly weathered soils with finely ground basalt rock. Applied Geochem. 17: 987 - 1001

Harley, A.D. 2002. Evaluation and improvement of silicate mineral fertilizers. (Ph.D thesis: The University of Western Australia).

Hinsinger, P., M.D.A. Bolland, and R.J. Gilkes. 1996. Silicate rock powder: effect on selected chemical properties of a range of soils from Western Australia and on plant growth as assessed in a glasshouse experiment. Fert. Res. 45: 69-79.

Huang, W.H. and W.D. Keller. 1970. Dissolution of rock-forming silicate minerals in organic acids: simulated first-stage weathering of fresh mineral surfaces. Am. Mineralogist 55: 2076-2094.

Huang, W.H. and W.C. Kiang. 1972. Laboratory dissolution of plagioclase feldspars in water and organic acids at room temperature. Am. Mineralogist 57: 1849-1859.

Hughes, J.C. and R.J. Gilkes. 1994. Rock phosphate dissolution and bicarbonate-soluble P in some soils from South-Western Australia. Aust. J. Soil Res. 32: 767-779.

Jones, D.L. 1998. Organic acids in the rhizosphere – a critical review. Plant Soil 205: 25-44.

Leonardos, O.H., W.S. Fyfe, and B.I. Kronberg. 1987. The use of ground rocks in laterite systems: an improvement to the use of conventional fertilizers? Chem. Geol. 60: 361-370.

Leonardos, O.H., S.H. Theodoro, and M.L. Assad. 2000. Remineralization for sustainable agriculture: a tropical perspective from a Brazilian viewpoint. Nutr. Cycl. Agroecosyst. 56: 3 – 9.

Priyono J. and R.J. Gilkes. 2004. Dissolution of milled-silicate rock fertilizers in the soil. Aust. J. Soil Res. 42: 441-448.

Priyono, J. 2005. Effects of high energy milling on the performance of silicate rock fertilizers (Ph.D Thesis: The University of Western Australia).

Thomas, G.W. 1982. Exchangeable cations. In A.L. Page, R.H. Miller, and D.R. Keeney (Eds.) Methods of soil analysis, Part 2, Chemical and microbiological properties. ASA, SSSA Inc. Publ., Mdison, Wisconsin. pp. 159-164.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37: 29-38.

Welch, S.S. and W.J. Ullman. 1996. Feldspar dissolution in acidic and organic solutions: compositional and pH dependence of dissolution rate. Geochem. Cosmochem. Acta 60: 2939-2948.

Zhang, H. and P.R. Bloom. 1999. Dissolution kinetics of hornblende in organic acid solutions. Soil Sci. Soc. Am. J. 63: 815-822.