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PHOSPHORUS ADSORPTION AND DESORPTION PROPERTIES OF MINNESOTA BASALT LUNAR SIMULANT AND LUNAR GLASS SIMULANT

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Phosphorus (P) adsorption and desorption characteristics of Minnesota Basalt Lunar Simulant (MBLS) and Lunar Glass Simulant (LGS) were evaluated. Results of P interactions with lunar simulants indicated that mineral and glass components adsorbed between 50 and 70% of the applied P and that between 85 and 100% of the applied P was desorbed. The Extended Freundlich equation best described the adsorption data ($r^2 = 0.92$), whereas the Raven/Hossner equation best described the desorption data ($r^2 = 0.97$). Kinetic desorption results indicated that MBLS and LGS released most of their P within 15 h. The expanded Elovich equation fit the data best at shorter times while t/Q_{DT} equation had a better fit at longer times. These results indicate that P does not strongly adsorb to the two simulants and that any P that was adsorbed was readily desorbed in the presence of anion exchange resin. This work suggests that multiple small applications of P (10–20 mg P kg⁻¹) should be added to the simulants to ensure adequate solution P for plant uptake and efficient use of P fertilizer.

CROPS will be grown in lunar soil at an astronaut tended-lunar base to produce food and oxygen, recycle carbon dioxide, and supply water (transpiration). Because plant essential nutrients will be a limiting component of a lunar Advanced Life Support System (ALSS), it is important to understand plant nutrient interactions with lunar soil. High concentrations of calcium (113,640 mg kg⁻¹), magnesium (45,230 mg kg⁻¹), and sulfur (300–1400 mg kg⁻¹) are present in lunar soil (Hossner and Allen 1989). Phosphorus (P) has been reported to occur in lunar rocks and soils, with an average concentration of 800 mg P kg⁻¹ (Hossner and Allen 1989). However, it is unknown how fertilizer P will interact with lunar soil when applied for plant growth.

Secondary minerals such as phyllosilicates, X-ray amorphous colloid material (e.g., allophane), iron and aluminum hydrous oxides, and calcium carbonate have been shown to be responsible for P adsorption in terrestrial soils, which results in less P being available for plant

growth (Sample et al. 1980; Sanchez and Uehara 1980). However, depending on the type of P bonding that occurs, P can be released (desorbed) into solution in the presence of a sink (e.g., plant root).

Quantity/intensity parameters are utilized to describe P adsorption/desorption relationships. Quantity (Q) refers to the amount of P adsorbed to the soil in the case of adsorption or the amount of P released from the soil in the case of desorption. Intensity (I) refers to the amount of P in solution. Phosphorus adsorption and desorption plots are obtained by graphing Q versus I . Adsorption or desorption buffering capacity can be obtained by plotting the derivative of the Q/I plot versus I . Buffering capacity is defined as the amount of P that is added or removed that changes the solution concentration by one unit (Raven and Hossner 1994a). A more general definition of buffering capacity is the ability of a soil to maintain P solution concentration when P is added or removed from the soil system.

Since lunar regolith is considered a national treasure and is only allocated in small quantities (mg), terrestrial analogs were utilized to understand how lunar soil interacts with plant nutrients. Research concerning plant interactions with lunar soil (Weete and Walkinshaw 1972; Walkin-

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shaw et al. 1973; Walkinshaw and Johnson 1971; Baur et al. 1974; Shay et al. 1974) and chemical-mineralogical interactions in terrestrial analogs have been performed (Easterwood et al. 1991; Oglesby et al. 1993; Tan and Henninger 1993; Eick et al. 1996), but work concerning P interactions has not been done. The objective of this research was to determine the P adsorption, desorption, and kinetic desorption characteristics of the Minnesota Basalt Lunar Simulant (MBLS) and the Lunar Glass Simulant (LGS). Quantity and intensity parameters were utilized to understand P interactions with lunar simulants.

MATERIALS AND METHODS

Lunar Simulants

Minnesota Basalt Lunar Simulant (MBLS) was obtained from a 1 to 2-m-thick by 50-m-long sill found along a rock face at an abandoned quarry in Duluth, Minnesota (Weiblen and Gordon 1988). This basalt is a suitable lunar soil simulant because its bulk chemical and mineralogical composition is similar to Apollo 11 mare soil sample 10084 (Weiblen and Gordon 1988).

Lunar glass simulant (LGS) was obtained from the Corning Glass Co. (Corning New York) and has a bulk chemical composition similar to the average of high titanium soil found at the Apollo 11 landing site (C. Galindo, 1994, NASA, Johnson Space Center, personal communication). The Corning Glass Co. modified a procedure outlined by Minkin et al. (1976) to produce LGS.

Both simulants were ground to have the same size distribution as Apollo sample 10084. However, lunar simulants are not exact replicates of lunar soil. For example, they do not contain certain components of lunar soil such as agglutinates. Agglutinates are particles made of lithic, mineral, and glass fragments melted together by heat generated during meteorite impacts and are extremely difficult and expensive to produce synthetically. Despite the lack of agglutinates, these simulants can be used to provide insight into P reactions in lunar soil.

Characterization

X-ray diffraction analysis of the simulants was performed using a Phillips diffractometer (Cu-K α X-ray tube). Chemical analysis included pH (McLean 1982), electrical conductivity (Rhoades 1982), exchangeable cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) (Thomas 1982), total P (Olsen and Sommers 1982; Jackson 1958), extractable P (1.4 M NH₄OAc and 0.025 M EDTA at pH 4.2) (TAES

1980), and oxalate (Sheldrick 1984) and sodium dithionite extractable iron (Mehra and Jackson 1960). Microbiological analysis consisted of bacterial (Zuberer 1994) and fungal (Parkinson 1994) counts. Physical properties determined were size distribution (Jackson 1969), wilting point, and field capacity (Cassel and Nielsen 1986).

Simulant Preparation

Phosphorus was added as KH₂PO₄ solution to triplicate simulant samples in 5-mL minibakers at rates of 0, 2.5, 5.0, 10, 15, 20, and 25 mg P kg⁻¹ for the adsorption experiments. The 10 mg P kg⁻¹ rate was utilized in the desorption and kinetic desorption experiments. Anion exchange resin weights and desorption times were varied. Simulant weight for the MBLS adsorption experiments was 1 g, and 2 g of MBLS were used for the desorption and kinetic desorption experiments. The LGS experiments used 0.75 g of material because of a limited supply. The P-treated samples were incubated in a glove box for 7 days for the adsorption and desorption experiments, and the kinetic desorption experiments were incubated for 8 days. Samples were incubated at field capacity (0.03 MPa moisture), 23 to 25°C, and 85 to 95% humidity. In an attempt to mimic the atmospheric conditions of the ALSS, the incubations were performed in CO₂, O₂, and N₂ concentrations of 0.1, 21.75, and 78.15%, respectively (D.W. Ming, 1992, NASA, Johnson Space Center, personal communication). All P analyses used the stannous chloride method (Jackson 1958).

Phosphorus Adsorption

Phosphorus adsorption experiments are modified slightly after methods described by Raven and Hossner (1994a). After incubation, the simulant was transferred into 150-mL beakers, with a 2:1 deionized water to simulant ratio. The samples were shaken for 1 h, and the solution was then filtered through a millipore filter (0.45 μ m) and subsequently analyzed for P. The amount of P adsorbed was determined by subtracting the amount of P in solution from the amount of native solution P plus added P. Native solution P was determined by analyzing the solution with the procedure outlined above with the exception that no P was added to the simulant.

The amount of P adsorbed (Q_A) was plotted versus solution P (I_A), and the Langmuir, Freundlich, Extended Freundlich, and Temkin equations (Barrow 1978) were used to describe the

data. Data points associated with $Q_A = 0$ were not used in the Langmuir and Freundlich equation regression analysis because $\ln(0)$ (Freundlich) and $I_A/0$ (Langmuir) are not real numbers.

Phosphorus Desorption

The Raven and Hossner (1993) method was utilized for the MBLs P desorption studies. Dowex 1-X8 saturated with HCO_3^- anion exchange resin contained within nylon mesh (Nitex 100% polyamide nylon fiber, mesh 3-210/36) was used in the desorption studies. The MBLs material was pre-equilibrated with 10 mg P kg^{-1} simulant under the conditions mentioned. After equilibration, MBLs was transferred into 150-mL vials with a 2:1 water to simulant ratio and shaken on an orbital shaker for 1 h. After shaking, resin bags containing 0, 0.001, 0.0042, 0.0075, 0.015, 0.025, 0.25, and 1 g of resin (dry weight) were added to triplicate simulant suspensions using 3 to 4 drops of chloroform to reduce microbiological activity. The suspensions were shaken for 72 h, and the resin bags were then removed and washed free of particles with deionized water. The resin bags were placed into 20 mL of 0.5 M NaCl and shaken for 30 min to desorb the P from the resin. The simulant suspensions were allowed to equilibrate for 1 h, centrifuged at 3000 r.p.m. for 10 min, and filtered through a millipore filter ($0.45 \mu\text{m}$).

The amount of P desorbed from MBLs was determined from the resin extract, whereas the solution concentrations were determined as in the adsorption experiments. Native labile-P was determined by the procedure outlined above, but with zero P added and using 1 g of resin. The amount of P desorbed (Q_D), compared with solution P (I_D), was fitted to the Raven and Hossner (1993), Barrow (1979), and Brewster et al. (1975) equations (Table 2). When the I_D measurements were below the detection limit, $0.001 \text{ mg P kg}^{-1}$ was used in the regression analysis.

Desorption Kinetics

The same procedure used in the desorption experiments was used in the kinetic desorption experiments, except that 1-g resin weights were used and the time of desorption was varied from 0.5 to 72 h. Triplicate samples for MBLs and duplicates for LGS were used.

Kinetic data were plotted as desorbed P (Q_{DT}) versus time (t). The first order, second order, two-constant (Elkhatib and Hern 1988), parabolic (Cooke 1966), and expanded Elovich (Raven and Hossner 1994b; Polyzopoulos et al.

1986) equations were used to describe the kinetic data (Table 3). Also used was the t/Q_{DT} equation, which plots t/Q_{DT} versus t , yielding the linear form of $t/Q_{DT} = a + bt$, which converts to $Q_{DT} = t/(a + bt)$ (Table 3). Because t/Q_{DT} was not a real number at $Q_{DT} = 0$, a value of 0.001 was used at 0 t and $0 \text{ mg P kg}^{-1} Q_{DT}$ in the t/Q_{DT} equation. The parameters (a, b) for the t/Q_{DT} equation came from the linear form. Once the parameters were obtained, they were used in the $Q_{DT} = t/(a + bt)$ equation, which was plotted and compared with the original data.

RESULTS

Characterization

Mineralogical analysis (XRD) indicated that MBLs contained anorthite, augite, and ilmenite. This is in agreement with other mineralogical analyses of MBLs (Tan and Henninger 1993;

TABLE 1
Characterization data for Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS)

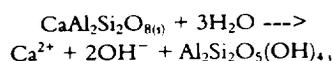
	MBLS	LGS
Size Fractions (mm)		% wt.
Sand>50	54.3	54.1
Silt 2-50	44.2	44.2
Clay<2	1.5	1.7
Moisture (MPa)		% wt.
0.03	8.5	9.4
1.5	0.9	1.5
Exchangeable Cation		cmol kg ⁻¹
Ca	0.53	0.47
Mg	0.21	0.17
K	0.06	0.04
Na	0.14	0.02
pH	9.30	9.75
		S m ⁻¹
E.C.	0.007	0.008
		mg kg ⁻¹
Oxalate Fe	12115	1684
DCB Fe	3715	359
Total P	140	417
Extractable P	28	†
Resin Desorbable P	1.18	0.78
Microbes		counts kg ⁻¹
Bacteria	1×10^5	1×10^5
Fungi	1×10^5	1×10^5

†Not determined.

Gordon 1991). Because of its glassy nature, the LGS material had no prominent X-ray peaks.

The simulants were ground to the same size distribution as Apollo 11 sample 10084. The size fraction data (Table 1) indicate that the simulants have a sandy loam texture according to the USDA textural triangle (Singer and Munns 1987). Because of the sandy nature of these simulants, field capacity (0.03 MPa) values were found to be low for both simulants (Table 1).

The elevated pH values found in MBLS and LGS (Table 1) can be explained by hydrolysis reactions of the primary minerals in MBLS (Stevens and Carron 1948; Stumm and Morgan 1981; Bohn et al. 1985) and alkali and alkaline cations in LGS. The hydrolysis of the MBLS mineral anorthite can be illustrated as follows (Stumm and Morgan 1981):



It should be noted that this model is being used solely to depict the increase in pH associated with the weathering of anorthite.

The term abrasion pH is defined as the pH of a mineral solution after that mineral has been ground in water (Stevens and Carron 1948). As the primary minerals are ground in water, hydrolysis reactions occur resulting in elevated pH values. Because the preparation of MBLS required grinding, similar effects associated with abrasion pH determination appear to have caused high pH values in MBLS.

These simulants were unweathered so they were not highly charged and, therefore, possessed low amounts of exchangeable cations (Table 1). Broken edges may have provided enough edge charge for limited cation exchange. The electrical conductivity (EC) of both simulants was low (Table 1), indicating that these simulants would not pose a salinity problem.

Dithionite-citrate-bicarbonate (DCB) extractable Fe values were lower than the oxalate extractable Fe (Table 1). This is contrary to extractable Fe values for most terrestrial soils. The DCB method is more suitable for removing oxidized Fe, and the oxalate method is more suitable for removing reduced and poorly crystalline Fe (Wang et al. 1991). Because the simulants were composed mostly of reduced Fe (MBLS) and poorly crystalline Fe (LGS) (Galindo et al. 1989), the DCB method was not expected to extract more Fe than the oxalate method.

Total P concentrations in the surface 8 inches of terrestrial soils have been found to range from

38 to 956 mg P/kg, with an average of 382 mg P/kg (Tisdale et al. 1985). The MBLS material fell below the average, whereas the LGS material exceeded the average (Table 1). Extractable P (Table 1) for MBLS was in the medium range. Resin-extractable P (Table 1) was higher in MBLS than in LGS. Because total P was higher in LGS than in MBLS, it appeared that LGS retained P more strongly than did MBLS.

Because the simulants lacked organic matter, microbial counts were low (Table 1) when compared with most soils (10^8 - 10^9 bacteria kg^{-1} , 10^8 - 10^{11} fungi kg^{-1}) (Alexander 1977).

P Adsorption

The data indicate that added P was not adsorbed strongly by the simulants (Fig. 1). From 80 to 100% of the added P was adsorbed at application rates below 5 mg P kg^{-1} . Only 50 to 70% of the applied P of the applied P was adsorbed at the 25 mg kg^{-1} treatment level. Most terrestrial soils would have continued to adsorb higher percentages of P beyond the 25 mg kg^{-1} treatment level. Texas soils, ranging from acid to slightly basic (Raven 1992), adsorbed 78 to 95% of P added at a rate of 25 mg P kg^{-1} . Volcanic ash soils from Guatemala retained 92 to 97% of the 929 mg P kg^{-1} applied P (Prasad and Motto 1982). Subtropical acid soils from Australia adsorbed

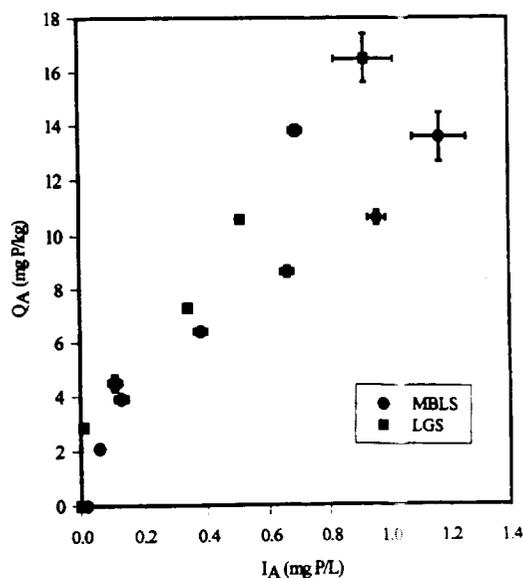


Fig. 1. Phosphorus adsorption data for Minnesota basalt lunar simulant and lunar glass simulant. Error bars represent standard deviation.

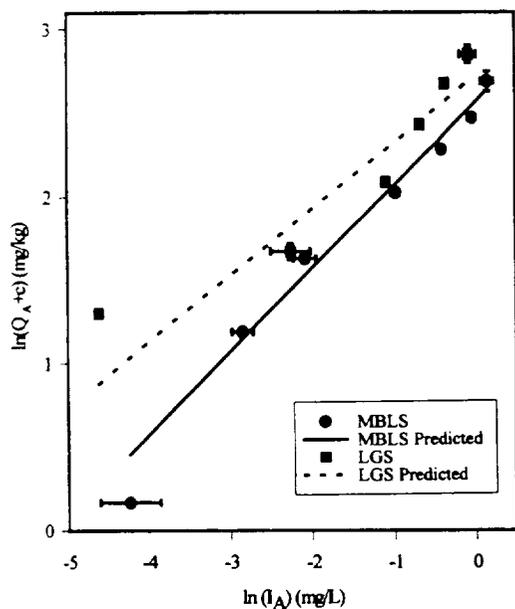


Fig. 2. Extended Freundlich plots of Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS). Error bars represent standard deviation. Error bars on some points are too small to be observed.

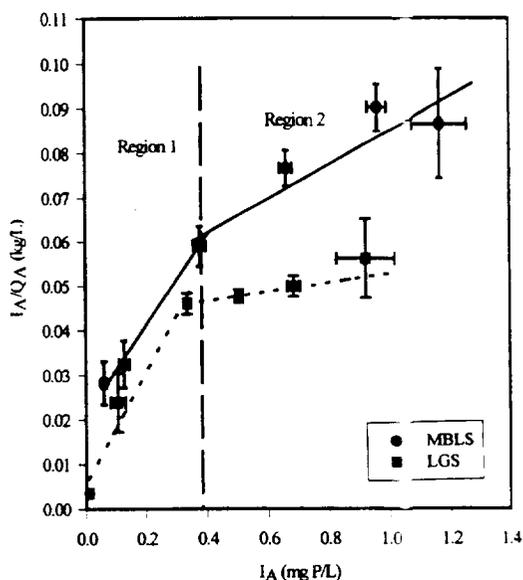


Fig. 3. A two-region Langmuir plot of I_A/Q_A versus I_A for Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS). Error bars represent standard deviation.

100% of added P (25 mg P kg^{-1}). When compared with other soils, it is evident that P was not strongly adsorbed to the simulants. However, sandy soils do not adsorb high amounts of P because of the lack of P-adsorbing minerals (secondary minerals). Secondary minerals (e.g., Fe and Al-hydrous oxides), which are largely responsible for P adsorption, were not detected in the simulants; therefore, P adsorption was not extensive.

All adsorption equations described P adsorption to the simulants (Table 2). However, the Extended Freundlich best described the adsorption data for both simulants (Fig. 2) because of the higher r^2 value. This indicates that the energy of adsorption decreased exponentially with increasing P adsorption (Bache and Williams 1971). The Extended Freundlich and the Freundlich equations both described the data equally well for MBLS, but the Extended Freundlich equation is favored because it accounts for native adsorbed P in the c term. The maximum adsorption capacities for MBLS and LGS as determined by the Langmuir equation (a term; Table 2) (Barrow 1978) were $17.2 \text{ mg P kg}^{-1}$ and $19.2 \text{ mg P kg}^{-1}$, respectively. When the P adsorption data were plotted in the Langmuir form (I_A/Q_A vs I_A), two-

region Langmuir plots were obtained (Fig. 3). It has been proposed that the two-region Langmuir plot indicates adsorption (region 1) and then precipitation (region 2) (Griffin and Jurinak 1978). Therefore, it is possible that P adsorption occurred up to about 0.40 mg P/L in MBLS and 0.3 mg P/L in LGS. Beyond these I_A values, the concentration of P in solution was high enough to cause precipitation of calcium phosphate.

The adsorption buffering capacity of both simulants was considered low when compared with selected Texas soils. Buffering capacities of Texas soils ranged from 37 to 252 L kg^{-1} at 0.1 mg P/L (Raven 1992), whereas MBLS and LGS had values of 20 L kg^{-1} and 24 L kg^{-1} , respectively (Fig. 4). A low adsorption buffering capacity indicates that these simulants have a limited ability to adsorb P and that adding P will result in elevated solution P concentrations.

Desorption Study

Desorption data for MBLS showed that 88% of total P (total P = native soluble P + applied P) was recovered with 1 g resin (Fig. 5). At the lowest resin treatment (0.025 g), 67% of the P was recovered from the MBLS material. Selected sandy soils from Niger (Wendt et al. 1993) released 28

TABLE 2
Equation parameters and statistical data describing P adsorption onto
Minnesota basalt humor simulant (MBLS) and lunar glass simulant (LGS)

	MBLS		LGS	
	Parameters	Statistics	Parameters	Statistics
Extended	$a = 13.0$	$r^2 = 0.97$	$a = 15.2$	$r^2 = 0.92$
Freundlich†	$b = 0.5$		$b = 0.4$	
$\ln(Q_A + c) = \ln a + b \ln(I_A)$	$c = 1.2$		$c = 0.8$	
Freundlich	$a = 11.5$		$a = 13.9$	
$\ln(Q_A) = \ln a + b \ln(I_A)$	$b = 0.6$	$r^2 = 0.97$	$b = 0.4$	$r^2 = 0.90$
Langmuir‡	$a = 17.2$		$a = 19.2$	
$I_A/Q_A = 1/a + b/ab$	$b = 2.0$	$r^2 = 0.89$	$b = 3.3$	$r^2 = 0.78$
Temkin	$a = 2.9$		$a = 2.3$	
$Q_A = a \ln(b I_A)$	$b = 46.0$	$r^2 = 0.90$	$b = 264.0$	$r^2 = 0.74$

Prob > F = 0.0001

† c = native adsorbed P

‡ a = max adsorbed P, b = binding energy constant

to 81% of applied P to resin from 10 mg P kg⁻¹ treatments. It should be noted that P recovery by Wendt et al. (1993) consider only the percent of applied P desorbed. Raven and Hossner (1993) obtained 67 to 79% desorption of applied and native desorbed P in the range of 0 to 100 mg P kg⁻¹. Calculations in this paper consider native desorbed P as well as added P when determining the percent P desorbed. Desorption data suggested that MBLS tends to release a higher per-

centage of applied P than do terrestrial soils.

Native P desorbed was determined to be 1.18 mg P kg⁻¹ for MBLS. Because MBLS did not desorb more than 11 mg P kg⁻¹ at the 10 mg P kg⁻¹ treatment level, it was evident that not all adsorbed P was recovered (Fig. 5). Barrow and Shaw (1977) reported that anion-exchange resin cannot extract all desorbable P from soil.

The Brewster et al. (1975), Barrow (1978), and Raven and Hossner (1993) equations were

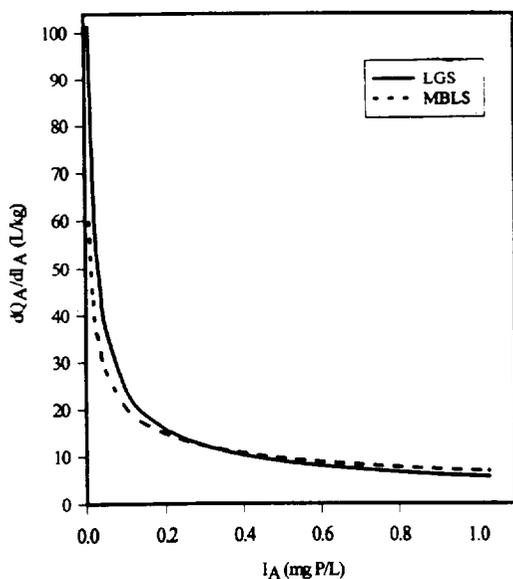


Fig. 4. Adsorption buffering capacity (dQ_A/dI_A) plots for Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS).

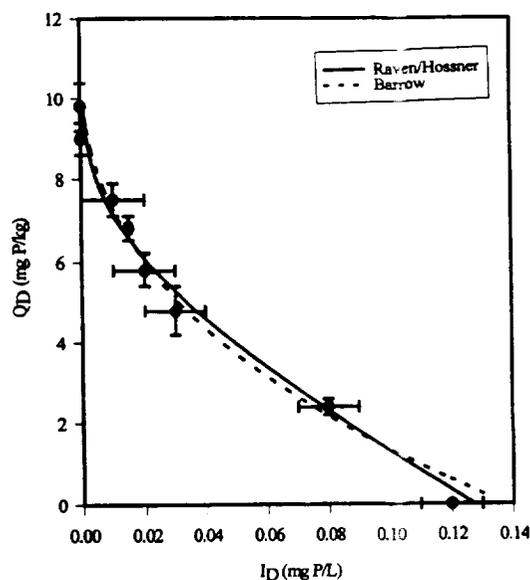


Fig. 5. Raven/Hossner and Barrow equations fitted to Minnesota basalt lunar simulant (MBLS) P desorption data. Error bars represent standard deviation.

TABLE 3
Equation parameters and statistical data describing P desorption from Minnesota basalt lunar simulant (MBLS) for the Raven/Hossner, Barrow, and Brewster equations

Equation	Parameters	Statistics
Raven/Hossner $Q_D = aI_D^{-0.01} + b \ln(I_D + 1) + c$	$a = 84.3$ $b = -44.7$ $c = -80.7$	$R^2 = 0.97$
Barrow $Q_D = a + bI_D^c$	$a = 10.0$ $b = 31.1$ $c = 0.5$	$r^2 = 0.97$
Brewster $Q_D = a + b \ln(I_D)$	$a = -1.5$ $b = -1.7$	$r^2 = 0.87$

Prob > F = 0.0001

utilized to describe the MBLS desorption data. The Barrow and the Raven and Hossner equations had the higher r^2 values (Fig. 5; Table 3). The Raven and Hossner equation would better describe desorption of P because it does not allow solution P to be reduced to 0 mg P/L.

The Raven and Hossner equation was used to determine the MBLS P desorption buffering capacity. By taking the derivative of the Raven and Hossner equation ($dQ_D/dI_D = -0.01 a I_D^{-1.01} + b/(I_D + 1)$) and plotting it versus I_D , a desorption buffering curve was developed (Fig. 6).

Buffering capacities of 480 L kg^{-1} at 0.01 mg P L^{-1} and 234 L kg^{-1} at 0.10 mg P L^{-1} were reported for selected Texas soils (Raven 1992). These buffering capacity values are $348 (0.01 \text{ mg P L}^{-1})$ and $185 \text{ L kg}^{-1} (0.10 \text{ mg P L}^{-1})$ higher than buffering capacity values of MBLS at those corresponding solution P values. The low desorption buffering capacity indicates that MBLS has a much lower ability to maintain solution P concentration as P was removed from solution compared with terrestrial soils. The MBLS desorption buffering curve indicates that MBLS easily released adsorbed P to the resin.

Kinetic Desorption Study

Most of the P was desorbed from both simulants within 15 h, similar to most terrestrial soils (Figs. 7 and 8). The MBLS material desorbed all of its P within 15 h, whereas LGS continued to desorb slightly more P with time. Most soils rapidly release P within 20 h and then continue to release P slowly over time (e.g., 90 h) (Raven and Hossner 1994b; Pavlatou and Polyzopoulos 1988; Evans and Jurinak 1976). The high total P (417 mg P kg^{-1}) in LGS apparently allowed continual desorption of P beyond 15 h.

The solution P values for both simulants were reduced to undetectable levels at 5 and 24 h for

MBLS and LGS, respectively. A slightly higher adsorption capacity and higher total P content allowed LGS to maintain solution P for a longer time than did MBLS.

The expanded Elovich and t/Q_{DT} equation, first and second order, parabolic, and two constant equations were fitted to the MBLS and LGS kinetic data. The expanded Elovich and the t/Q_{DT} equations were found to have the higher r^2 values and, therefore, best describe the kinetic data for both simulants (Table 4 and 5). The t/Q_{DT} equation possessed higher r^2 values than the expanded Elovich for both simulants. The expanded Elovich equation described the data best

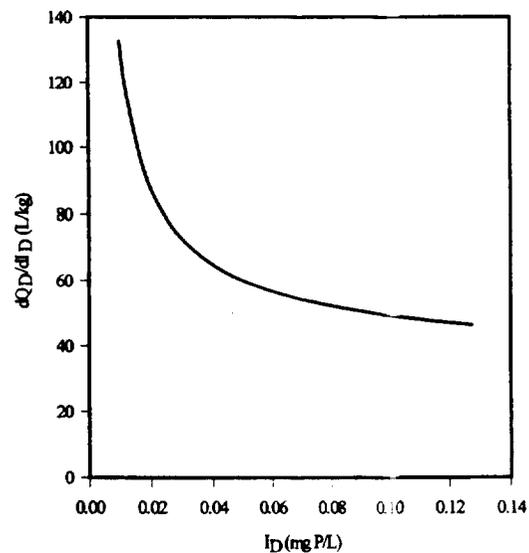


Fig. 6. Phosphorus desorption buffering capacity (dQ_D/dI_D) calculated from the Raven/Hossner desorption equation versus P remaining in solution (I_D) for Minnesota basalt lunar simulant.

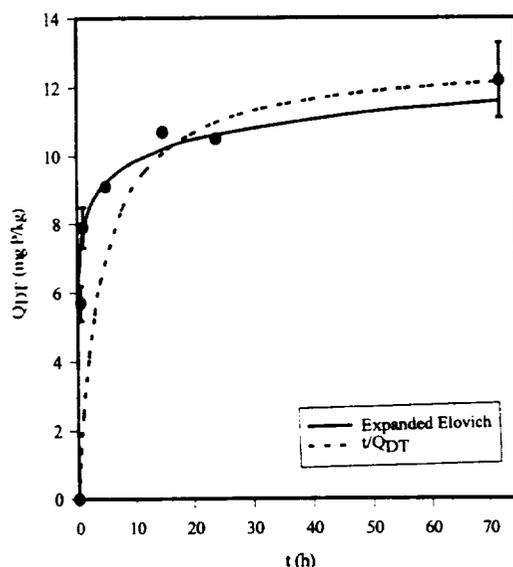


Fig. 7. Kinetic P desorption data showing the Expanded Elovich and t/Q_{DT} plots for the lunar glass simulant (LGS) with amount of P desorbed (Q_{DT}) as a function of time (t). Error bars represent standard deviation. Error bars on some points are too small to be observed.

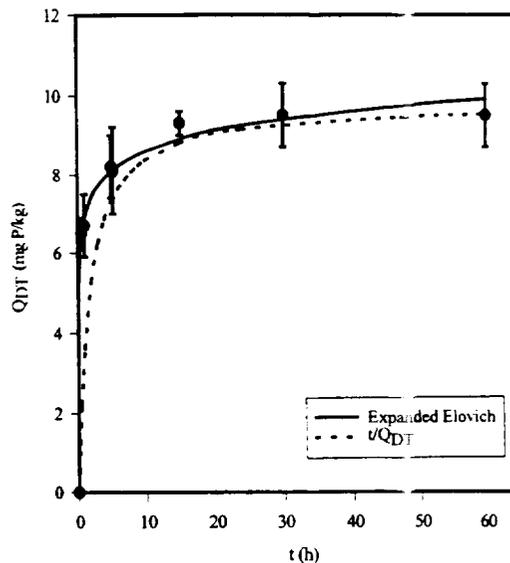


Fig. 8. Kinetic P desorption data showing the Expanded Elovich and t/Q_{DT} plots for the Minnesota basalt lunar simulant (MBLS) with amount of P desorbed (Q_{DT}) as a function of time (t). Error bars represent standard deviation.

at shorter times (<24 h LGS; <30 h MBLS), whereas t/Q_{DT} was better at longer times (>24 h LGS; >30 h MBLS) (Figs. 7 and 8).

DISCUSSION AND SUMMARY

The adsorption data indicated that the simulants did not adsorb applied P readily. The Extended Freundlich equation best described the P adsorption data, indicating that the energy of adsorption decreased exponentially with concentration. Interpretation of the Langmuir plots suggests that P was adsorbed onto the simulants up to about 0.40 and 0.30 mg P L⁻¹ in MBLS and

LGS, respectively, and that P began precipitating beyond these solution P concentrations. The adsorption buffering capacity data show that both simulants possess low adsorption buffering capacities, indicating that added P will not be adsorbed strongly and will result in elevated solution P concentrations. These data agrees well with P adsorption data of sandy soils, where low additions of P are required to obtain optimal solution P concentrations (Olsen and Watanabe 1970; Wendt et al. 1993)

The MBLS desorption data were best described by the Raven and Hossner equation. The

TABLE 4
Parameters and statistical data for Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS) kinetic desorption equations. Coefficient of determination (r^2) for the t/Q_{DT} equation is from its linear form

Equation	MBLS		LGS	
	Parameters	Statistics	Parameters	Statistics
Expanded Elovich	$a = 0.7383$	$r^2 = 0.94$	$a = 0.8956$	$r^2 = 0.96$
	$b = 0.0001$		$b = 0.0001$	
	$c = 6.8964$		$c = 7.7796$	
	$d = 1.0000$		$d = 1.0000$	
t/Q_{DT}	$a = 0.1716$	$r^2 = 0.98$	$a = 0.3185$	$r^2 = 0.97$
	$b = 0.1022$		$b = 0.0778$	

Prob > F = 0.0001

TABLE 5

Statistical data for Minnesota basalt lunar simulant (MBLS) and lunar glass simulant (LGS) kinetic desorption equations

Equation	MBLS		LGS	
	r^2	Prob > F	r^2	Prob > F
First order	0.31	0.0018	0.63	0.0019
Second order	0.00	0.7965	0.01	0.7115
Parabolic	0.48	0.0001	0.63	0.0007
Two constant	0.72	0.0002	0.83	0.0001

anion exchange resin desorbed a high percentage of P from the MBLS, indicating that P adsorption to the simulants is mostly reversible. The desorption buffering capacity indicated that MBLS desorbed most of its adsorbed P to the solution for uptake by the resin.

Kinetic data show that MBLS and LGS released most of the adsorbed P within 15 h. The LGS material desorbed more P than was added, indicating that some soluble P was being supplied by the crystal phase.

X-ray photoelectron studies have shown that iron (Fe) and aluminum (Al) hydroxides have constituted concentrations up to 4.2% and 12%, respectively, in a wide range of basalts (White and Hochella 1992). Because surface adsorption of P onto mineral surfaces is apparently attributable to iron and aluminum hydroxides, the low concentrations of surface Fe and Al hydroxides would not allow large scale P adsorption.

Unweathered volcanic ash soils (noncrystalline colloids) with high Si solubility have been shown to have low P adsorption capacity (Fox 1974). As the volcanic soils weathered and the Si solubility decreased, P adsorption increased in these volcanic soils (Fox 1974). Similar to unweathered volcanic soils, the low P adsorption capacity of LGS may possibly be a consequence of soluble Si, which forms silicate species that block P adsorption sites (Clark and McBride 1984; Eick et al. 1996). A low concentration of Fe and Al at the surface may also contribute to the limited P adsorption capacity of LGS.

The data indicate that P will interact with the mineral and glass fraction of lunar soil in a similar manner if P is added to lunar soil in an ALSS environment. There are other components of lunar soil (e.g., agglutinates) that are not represented in the simulants, and their reactions with P are unknown. However, by attempting to simulate a component of lunar soil, we can begin to understand how P interactions with lunar soil proceed. The data suggest that obtaining the most efficient P fertilization of lunar soil would require a small P

application (e.g., 10–20 mg P kg⁻¹) before planting, followed by similar treatments applied during crop growth. This fertilization scheme is based on wheat growth experiments (data not shown) and will vary according to the crop to be grown. This recommendation agrees well with the optimal P application of 10.2 mg P kg⁻¹ required for millet growth in sandy soils of Niger (Wendt et al. 1993). Because the simulants had a low P adsorption capacity, one large P treatment (e.g., 100 mg P kg⁻¹) to lunar soil may put more P in solution than is required for plant growth, thereby promoting inefficient use of P fertilizer and nutrient imbalances (e.g., Fe, Mn, Zn) in the plant. As crops are grown in the lunar soil, the formation of secondary minerals (e.g., Fe-hydroxides, clays) will result (Easterwood et al. 1991), and the P adsorption and desorption characteristics of lunar soil will change over time. Therefore, understanding P interactions in lunar soil will be an evolving challenge for agronomists.

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