Phosphate and Potassium Retention and Release during Chrysanthemum Production from Precharged Materials: II. Calcined Clays and Brick Chips

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ABSTRACT. Soilless container media have almost no capacity to retain PO₄ or K. The nutrient retention of two calcined clays, attapulgite and arcillite, and brick chips, precharged with PO₄ and K, was investigated. These could serve as an alternative slow-release fertilizer when incorporated into a soilless medium as a component of the mix. Sorption curves were developed at 25 °C for attapulgite of two particle sizes (0.8 to 1.6 mm and 1.6 to 3.2 mm), arcillite (1.1 to 3.2 mm), screened pieces of brick (1.0 to 3.6 mm), and a medium of 7 sphagnum peat : 3 perlite (v/v) using solutions of KH₂PO₄ (P at 0 to 20,000 mg L⁻¹). Curves indicated that PO₄ and K sorption were similar for both particle sizes of attapulgite, so only the larger size [1.6 to 3.2 mm (8 to 16 mesh)] was used in greenhouse studies. Materials were evaluated in greenhouse studies by growing 'Sunny Mandalay' chrysanthemum [*Dendranthema ×grandiflora* Kitam. (syn. *Chrysanthemum ×morifolium* Ramat.)]. The precharged materials were tested at 10%, 20%, and 30% by volume of a peat : perlite root medium. Phosphate, K, and pH were determined on unaltered medium solutions collected throughout the cropping cycle and foliar analyses were determined on tissue collected at midcrop and end of the crop. Data indicated that precharged calcined clays retained and released PO₄, and to some degree K, over time. Precharged clays did not provide K at levels which met plant needs during the latter half of the cropping cycle, but it was released and used at appreciable levels during the first month of crop production. Growth of plants receiving PO₄ solely from precharged attapulgite and arcillite at 20% of the medium volume was not significantly different from that of a commercial control when the leaching fraction was maintained at 0.2. However, release of PO₄ from the brick chips was not enough to match plant demand. Phosphate lost through leaching from the precharged clays was reduced by about two-thirds compared to control plants fertilized with P at 46.5 mg L⁻¹ from water-soluble fertilizer at each watering.

Soilless media, commonly used for container production, consist of high percentages of sphagnum peat or pine bark that have virtually no ability to adsorb and retain PO₄ (Marconi and Nelson, 1984) in addition to a limited capacity for retention of K. The soil-based mixes used before the introduction of soilless media often had substantial PO₄ retention and cation exchange capacities. However, use of soil in mixes lost popularity for a number of reasons, including the need for, and cost associated with, pasteurization and difficulty in securing consistent, high-quality sources (Nelson, 1998).

If a container medium component with high capacity to fix PO₄ and/or adsorb cations like K was precharged with these nutrients before incorporation into the mix, this component could serve as a slow-release fertilizer. This would have to maintain equilibrium concentrations of these nutrients in the root medium solution at levels required to meet plant uptake over the course of the cropping cycle. Ideally, this nutritional system would offer the advantage of

decreased PO₄ and K losses in the leachate. Most of these nutrients would be retained on a medium component, while only a small proportion would reside in the medium solution subject to leaching. Such a system could also eliminate the need to use PO₄ in the liquid fertilization program.

Clays and other constituents derived from soils may serve as root medium components and can be precharged with nutrients. Clays have varying capacities to retain PO₄ and cations. For example, 1 : 1 layer silicate clays such as kaolinite consist of alternating silica (tetrahedral) and octahedral sheets. They generally possess a substantial ability to retain PO₄, primarily through inner-sphere (covalent) surface complexing at edge surfaces (McBride, 1994). In contrast, 2 : 1 layer silicate clays such as montmorillonite consist of an octahedral sheet sandwiched between two tetrahedral sheets. They generally possess substantial cation exchange capacity, which arises from isomorphic substitution and pH-dependent deprotonation of -OH in the layer silicates. They have a lower capacity for PO₄ binding (on a weight basis). Fixation of K, which has an ionic radius that allows it to fit into the siloxane ditrigonal cavity on the basal surface of layer silicates (Sposito, 1989), results from K⁺ entrapment between collapsed layers of 2 : 1 minerals, such as vermiculite (McBride, 1994).

Calcined, or baked, clays could be used to provide structure in a soilless medium and eliminate the need for pasteurization associated with the use of soil. In addition, they could be used at particle sizes which would not interfere with the beneficial physical properties of soilless media. In fact, some waste materials, such as broken pieces of brick, a waste product resulting from the manufacture of brick, may be used for the purpose described.

Warren and Bilderback (1992) studied arcillite, a 2 : 1 calcined clay, at varying percentages of amendment in a pine bark-based medium. They found that P, K, and NH₄ concentrations in the root

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Table 1. Exchangeable cations and P extracted from the calcined clays, attapulgite and arcillite, and from brick chips before charging with K and PO_4 from KH_2PO_4 .

Material	K	Na	Ca	Mg	P
	(mg·cm ⁻³)				(μg·cm ⁻³)
Attapulgite, small ^z	0.42	0.09	3.46	1.93	77.9
Attapulgite, large ^y	0.63	0.09	2.77	2.57	121.9
Arcillite	0.86	0.12	1.77	0.37	18.8
Brick chips	0.03	0.06	0.97	0.01	44.1

^z0.8 to 1.6 mm.

^y1.6 to 3.2 mm.

medium derived from the slow-release fertilization program increased with increasing arcillite rate, suggesting that arcillite improved retention of these ions by the medium. Hiller and Koller (1979) reported that arcillite had a high natural content of K and B. Carlile and Bedford (1988) mixed a calcined clay screened from crushed brick waste with peat and observed that P concentrations were reduced and Ca concentrations were higher in media containing the clay, compared to a nontreated control. These authors did not speculate about the cause of the reduced P levels, but explanations may have been PO_4 sorption by the clay component or reduced PO_4 solubility. Therefore, the objectives of this research were to 1) characterize release of PO_4 and K from precharged calcined clays and brick chips used as a component of a soilless medium over the course of a 10-week cropping cycle, 2) determine the quantity of soluble PO_4 leached over time from these media, and 3) determine the effectiveness of these precharged materials at providing PO_4 and K during production of chrysanthemum.

Materials and Methods

TREATMENT MATERIALS. Two commercial calcined 2 : 1 clays, attapulgite and arcillite, were used in this study. Low volatile matter (<3% moisture) attapulgite (trade name Fuller's Earth) was provided by Floridin Co., Quincy, Fla., at two particle sizes: 0.8 to 1.6 mm (small; 16 to 30 mesh), and 1.6 to 3.2 mm (large; 8 to 16 mesh). Attapulgite is used commonly as a carrier and diluent for granular formulations of pesticides. Only the large particle size was tested in the greenhouse experiments. Arcillite (trade name Turface, Applied Industrial Materials Corp., Deerfield, Ill.) is a calcined product of the combined clays montmorillonite and illite. Particle size studied was 1.1 to 3.2 mm (8 to 24 mesh). Brick chips consisted of a commercial product marketed under the trade name Brickscape (Cherokee Sanford Group, Inc., Sanford, N.C.) that was screened to a particle range of 1.0 to 3.6 mm (7 to 25 mesh).

LABORATORY EXPERIMENTS. Mineral extractions were conducted on attapulgite, arcillite, and brick chips to determine concentrations of P, K, Na, Ca, and Mg present before sorption. Results of initial levels of P and K present in the materials were incorporated into curve calculations. A dilute HCl and H_2SO_4 method was used for P extraction (Olsen and Sommers, 1982) and K, Na, Ca, and Mg were extracted with NH_4OAc (Knudsen et al., 1982) (Table 1). Phosphate and K adsorption curves were created by modifying the procedures described by Fox and Kamprath (1970) and used to select treatments for the greenhouse studies (see Williams et al., 2000).

GREENHOUSE EXPERIMENTS, GENERAL PROCEDURES. The two experiments in which the clay materials were tested were described previously (Williams et al., 2000). Experimental materials and procedures that were common to both papers included culture of 'Sunny Mandalay' chrysanthemum; basic physical components of the root medium and preplant amendments; planting, sampling, and

harvest dates; and sampling and analytical methods of root medium solution and plant tissue. The following additional procedures were used. Attapulgite, large particle size; arcillite; and brick chips were precharged with PO_4 and K from P at 2050, 1595, or 275 mg L⁻¹, respectively, from KH_2PO_4 .

Treatments were arranged in randomized complete block designs with three blocks and two pots per experimental unit. Data were subjected to analysis of variance procedures (PROC ANOVA, SAS Inst., Cary, N.C.). Least significant differences (LSDs) were calculated to compare means. If the percentage clay by fertilizer treatment interaction was significant, a single LSD was calculated to compare means across both percentage clay levels and fertilizer treatments. If the percentage clay by fertilizer interaction was not significant, two separate LSDs were calculated, one to compare means across percentage clay levels and another to compare means across fertilizer treatments.

GREENHOUSE EXPERIMENT 1: PHOSPHATE AND K RELEASE FROM PRECHARGED ATTAPULGITE, ARCILLITE, AND BRICK CHIPS. Three control treatments were used, each receiving N at 210 mg L⁻¹ of the following fertilizers at each watering: the complete fertilizer consisted of 4.5 mM KNO_3 , 1.5 mM $\text{NH}_4\text{H}_2\text{PO}_4$, and 4.5 mM NH_4NO_3 (2 $\text{NH}_4\text{-N}$: 3 $\text{NO}_3\text{-N}$); the -P fertilizer consisted of 4.5 mM KNO_3 and 5.25 mM NH_4NO_3 (7 $\text{NH}_4\text{-N}$: 13 $\text{NO}_3\text{-N}$); and the -K fertilizer consisted of 1.5 mM $\text{NH}_4\text{H}_2\text{PO}_4$ and 6.75 mM NH_4NO_3 (11 $\text{NH}_4\text{-N}$: 9 $\text{NO}_3\text{-N}$). The leaching fraction (LF), defined as the volume of leachate divided by the volume of solution applied, was estimated at 0.2. Plants were watered just as the first plants began to develop visible symptoms of water stress.

Control plants were grown in a medium of 7 low-humified sphagnum peat (Sun Gro Horticulture, Inc., Bellevue, Wash.) : 3 coarse perlite (Krum, Silbrico Co., Hodgkins, Ill.) (v/v). Test materials were incorporated into the medium as 10% or 30% of the volume of the mix by replacing perlite. These large volumes were used in an effort to decrease the occurrence of zones of localized PO_4 depletion in the rhizosphere. The treatment structure was a 2 × 2 × 3 factorial of two clays (attapulgite and arcillite) by two incorporation proportions (10% and 30% of the medium) by three fertilizer treatments (complete fertilizer with uncharged clays, -P fertilizer with precharged clays, and -K fertilizer with precharged clays). Only two treatments with brick chips were tested: complete fertilizer with uncharged brick chips comprising 30% of the medium and -P fertilizer with precharged brick chips comprising 30% of the medium. The experimental design was a randomized complete block with three blocks and two pots per experimental unit.

GREENHOUSE EXPERIMENT 2: PHOSPHORUS BUDGET. Two fertilizer treatments were used: the complete fertilizer was identical to the formulation used in Expt. 1 and the -P fertilizer consisted of 4.5 mM KNO_3 , 4.5 mM NH_4NO_3 , and 0.75 mM $(\text{NH}_4)_2\text{SO}_4$. Both fertilizers contained 2 $\text{NH}_4\text{-N}$: 3 $\text{NO}_3\text{-N}$. Plants were watered when the weight of the pots decreased by 40% of container capacity. A measured

Fig. 1. (A) Phosphate and (B) K adsorption curves and (C) pH of supernatants during adsorption for the control medium, attapulgite at two particle sizes, small (0.8 to 1.6 mm) and large (1.6 to 3.2 mm); arcillite; and brick chips. In each figure the SE ($n=3$) for every data point is smaller than the graphed symbol; (■) control medium; (●) attapulgite, large; (○) attapulgite, small; (□) arcillite; and (◆) brick chips.

volume of fertilizer solution containing N at 210 mg L⁻¹ was applied at each watering to result in a controlled LF of 0.2.

Control plants were grown in the same medium as Expt. 1, 7 peat : 3 perlite (v/v). Precharged attapulgite and arcillite were incorporated into the medium to comprise 20% of the volume and peat : perlite ratios were adjusted to result in physical properties more similar to the control treatments: 6.5 peat : 1.5 perlite : 2 precharged clay (v/v). The precharged brick chips were again tested at 30% of the volume of the mix, but the ratio of components was altered to 6 peat : 1 perlite : 3 brick chips (v/v).

Results and Discussion

LABORATORY EXPERIMENTS. Adsorption data indicated that 7 peat : 3 perlite medium (v/v) had almost no facility to retain PO₄ and only limited ability to retain K in the pH range of supernatants encountered in this study (Fig. 1A and B). Potassium retention was sizeable in both attapulgite and arcillite, which was predictable based on the 2 : 1 structure of these clays. Attapulgite had a remarkable facility to retain PO₄. Attapulgite retention of PO₄ was up to five times greater than arcillite at the highest rate of charge (Fig. 1A). The nearly overlapping curves for attapulgite treatments of large and small particle sizes suggested only a slight difference in their capacity to retain PO₄, especially at the lower levels of charge, and even less difference in their ability to retain K (Fig. 1A and B); thus, the larger of the two particle sizes was chosen for testing in the greenhouse studies.

The PO₄ adsorption curves for brick chips indicated a potential for PO₄ retention. However, K retention by this material was lower than that of the peat : perlite medium, so K retention by brick chips was not studied in greenhouse experiments (Fig. 1). The pH levels measured in the supernatants suggested that attapulgite might raise the pH level in the root medium and that arcillite and brick would have less influence on pH (Fig. 1C).

GREENHOUSE EXPERIMENT 1. Statistical analysis of the factorial treatment set of calcined clays indicated no significant difference in results of plant growth characteristics between attapulgite and arcillite (Table 2). However, the fertilizer treatment was highly significant for all growth characteristics. Treatment means showed that plants relying on precharged clays to meet their K needs did not

produce growth equivalent to other treatments. Percent (by volume) of the clay amendment which comprised the root medium resulted in significantly different results for three of the five growth characteristics. However, the direction of the effect of the clay proportion in the medium varied among fertilizer regimes. For example, precharged attapulgite with -P fertilizer at 10% of the mix resulted in slightly better growth than attapulgite at 30% of the mix. The opposite tended to be true for the precharged with -K fertilizer and uncharged attapulgite treatments. These relationships explain the significant percentage (Pct) × fertilizer (Fert) interaction, which was the only consistently significant interaction (Table 2).

Plants that received PO₄ only from precharged calcined clays and brick chips had slightly reduced growth compared to the complete control (Table 2). At midcrop, tissue P levels (Table 3) of these treatments were above the accepted standard minimum critical level of 0.25% (Mills and Jones, 1996). By end of the crop, the P levels of these treatments met the minimum critical value of 0.20% (Mills and Jones, 1996) except brick chips which resulted in a tissue P level of 0.19%. Another reason to consider the P tissue concentrations adequate is that the standards are based on analysis of recently matured leaves, while the tissue analyzed at end of the crop in this study was whole shoots. One would expect whole shoots to have lower tissue concentrations of the mobile nutrients N, P, K, and Mg compared to leaves due to dilution from stem, flowers, and older foliage. The higher tissue concentrations found in the complete control suggested luxury consumption of PO₄ from high application rates of the complete fertilizer. In the complete control and plants grown with 10% and 30% precharged calcined clays and brick chips with -P fertilizer, adequate levels of all other essential nutrients were found at the midpoint (data not presented) and end of the crop. This includes S and B, which were spot-checked (data not presented). A few exceptions were noted for Ca and Cu at end of the crop, but these levels surpassed the complete control concentrations, which showed no signs of deficiency. Thus, it could be argued that reduction in growth of plants grown with precharged calcined clays and -P fertilizer was not likely due to mineral nutrient deficiency. The possible exception was brick chips.

The root medium solution PO₄ concentrations for plants grown with precharged calcined clays and brick were apparently adequate throughout the cropping cycle, with solution PO₄-P concentrations

remaining above the minimum critical level of 0.2 mg·L⁻¹ established by Nishimoto et al., (1975) (Fig. 2A and B). The sole exception was observed for precharged brick chips on day 70 of the cropping cycle, when PO₄-P levels in the medium solution were 0.1 mg·L⁻¹. The PO₄ levels in the root medium solution were substantially higher from precharged clays which comprised 30% of the medium compared to those of media with 10% clay. It is important to note that the solution nutrient concentrations are a snapshot of levels in solution. During the 1-h period between irrigation and solution sampling, the PO₄ levels would also be affected by plant uptake. As the plants became larger over the course of the cropping cycle, they were able to deplete the medium solution of nutrients faster.

The high pH of the medium solutions after the first month of the cropping cycle for plants fertilized with the -P fertilizer as compared

to the complete control (Fig. 2E and F) may explain part of the reduced growth resulting from use of precharged attapulgite, arcillite, and brick chips. High pH may result in decreased availability of PO₄ or micronutrient cations. While the high pH levels could have resulted directly from the clays and brick themselves, it might also have been influenced by differences in fertilizer formulations of the complete and -P fertilizers. The complete fertilizer contained a higher percent NH₄-N than the -P fertilizer, which would tend to adjust the pH downward over the course of the cropping cycle. In Expt. 2, these fertilizers were altered to provide the same NH₄:NO₃ ratio; the ions which were varied were Ca and SO₄.

Physical properties may also have played a role in reducing the growth of plants grown with precharged clays and brick at 10% and 30% of the medium. The mixes in which the clay comprised 30% of the volume and replaced all perlite had a finer texture than the

Table 2. Growth measurements for shoot growth at the end of the crop (day 71) of 'Sunny Mandalay' chrysanthemums grown with attapulgite, arcillite, and brick chips comprising 10% and 30% of the medium, and a peat-based control medium (Expt. 1).

Source	Mix (%)	Ht (cm)	Width (cm)	Fresh wt (g)	Dry wt (g)	Rating ^z
Control medium						
Complete fertilizer ^y		20.2	30.0	162.6	16.3	10.0
-P fertilizer		8.0	8.5	6.4	1.0	1.0
-K fertilizer		10.4	15.4	39.2	3.0	1.7
LSD _{0.05} ^x		1.8	3.1	24.5	3.1	1.8
-P fertilizer, precharged clays						
Attapulgite	10	19.0	27.4	133.2	15.2	9.7
	30	17.8	27.3	124.7	12.0	8.7
Arcillite	10	19.1	27.8	113.3	14.2	8.7
	30	19.0	28.1	129.5	13.7	9.3
Brick chips	30	18.8	25.7	100.6	11.7	9.0
-K fertilizer, precharged clays						
Attapulgite	10	16.3	22.5	78.9	8.7	4.0
	30	17.5	25.5	97.2	9.7	6.3
Arcillite	10	15.4	22.8	74.9	8.1	4.3
	30	18.3	27.5	103.5	11.1	7.7
Complete fertilizer, uncharged clays						
Attapulgite	10	18.8	30.1	144.8	12.1	9.3
	30	20.3	30.4	146.7	14.1	8.7
Arcillite	10	19.5	30.9	161.2	15.9	10.0
	30	19.6	29.8	138.5	15.1	8.7
Brick chips	30	20.3	30.1	147.6	15.8	10.0
LSD _{0.05} ^w		1.4	2.5	21.8	2.7	1.0
Significance ^v						
Percent volume of clay in medium: 10% or 30% (Pct)						
Fertilizer applied: -P, -K, or complete (Fert)						
Calcined clay: attapulgite or arcillite (Clay)						
Pct		*	*	NS	NS	*
Fert		***	***	***	***	***
Clay		NS	NS	NS	NS	NS
Pct × Fert		**	**	**	*	***
Pct × Clay		NS	NS	NS	NS	NS
Fert × Clay		NS	NS	NS	NS	NS
Pct × Fert × Clay		NS	NS	*	NS	NS

^zScale of 1 to 10 with 1 = death and 10 = optimum commercial growth.

^yComplete control.

^xLSD used to compare clay treatments within a given fertilizer treatment (-P, -K, or complete) to the control medium.

^wLSD used to compare brick chips means of both -P and complete fertilizer treatments with other treatment means.

^vFactorial treatment analysis of two calcined clays × two percentage of mix × three fertilizers.

NS, *, **, *** Nonsignificant or significant at *P* = 0.05, 0.01, or 0.001, respectively.

control resulting in reduced air-filled porosity and increased water retention (Table 4). This difference was accentuated by watering all plants on the same schedule so that smaller plants were watered too often. The mixes were reformulated for Expt. 2 by adjusting the peat to perlite ratios to yield a coarser texture thereby increasing the air-filled porosity in the mixes containing clays.

Although the LF was estimated to be 0.2 in Expt. 1, the method of watering did not allow for careful control. This could have resulted in excessive loss of PO_4 which would not have occurred

with a lesser LF or subirrigation. In Expt. 2, to improve the accuracy of leaching and to water each treatment based on the individual need of those plants, water was applied by precise weight measurements as described previously. Thus, any differences in available water of the different media were balanced.

Growth of plants that relied on precharged clays to meet their K requirement was significantly less than the complete control (Table 2). Symptoms indicative of K deficiency, including necrotic lesions on the lower foliage, were observed on the treatment plants. The

Table 3. Phosphorus and K content (dry weight basis) of the youngest fully expanded leaves collected at midcrop (day 43) and mineral content of whole shoots at end of the crop (day 71) of 'Sunny Mandalay' chrysanthemums grown with attapulgite, arcillite, and brick chips comprising 10% and 30% of the medium, and a peat-based control medium (Expt. 1).

Source	Mix (%)	Midcrop		End crop								
		P	K	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
		(%)						(μg g ⁻¹)				
Control medium												
Complete fertilizer ^z		0.90	5.39	4.40	0.84	4.29	0.96	0.53	63	194	93	9
–P fertilizer		0.06	3.52	3.23	0.14	3.18	0.65	0.27	74	116	214	5
–K fertilizer		0.88	1.06	5.65	1.04	0.66	2.00	1.12	97	266	361	9
LSD _{0.05}		0.16 ^y	1.0 ^y	0.62 ^y	0.15 ^y	0.41 ^x 0.40 ^w	0.26 ^y	0.14 ^y	NS	37 ^y	66 ^y	NS ^x 1 ^w
–P fertilizer, precharged clays												
Attapulgite	10	0.43	5.92	3.76	0.32	4.35	1.17	0.45	60	97	56	3
	30	0.61	6.04	4.02	0.55	4.92	1.26	0.46	87	108	43	7
Arcillite	10	0.29	6.34	3.42	0.20	3.95	1.01	0.40	82	116	107	7
	30	0.49	6.28	3.74	0.42	4.41	1.20	0.38	84	123	58	8
Brick chips	30	0.31	5.87	3.32	0.19	4.00	1.14	0.37	89	111	110	7
–K fertilizer, precharged clays												
Attapulgite	10	1.21	1.02	4.99	1.02	0.79	1.93	1.14	79	170	119	8
	30	1.08	3.13	4.52	0.92	2.05	1.64	0.91	74	152	53	9
Arcillite	10	1.12	0.95	5.36	1.02	0.82	1.92	1.00	83	181	180	10
	30	0.98	2.02	4.50	0.94	1.32	1.69	0.88	73	167	82	9
Complete fertilizer, uncharged clays												
Attapulgite	10	0.71	5.76	4.40	0.66	4.71	0.88	0.50	84	165	35	7
	30	0.61	6.65	4.39	0.66	4.53	0.80	0.54	74	166	36	10
Arcillite	10	0.78	6.33	4.22	0.75	4.48	1.02	0.47	95	189	57	11
	30	0.73	6.06	4.66	0.75	4.55	1.14	0.50	90	222	51	10
Brick chips	30	0.86	5.72	4.70	0.77	4.57	1.19	0.46	95	215	61	10
LSD _{0.05} ^v		0.06	0.50	0.52	0.07	0.74	0.19	0.11	NS	28	45	2
Significance ^u												
Percent volume of clay in medium: 10% or 30% (Pct)												
Fertilizer applied: –P, –K, or complete (Fert)												
Calcined Clay: attapulgite or arcillite (Clay)												
Pct		NS	***	NS	**	***	NS	NS	NS	NS	***	*
Fert		***	***	***	***	***	***	***	NS	***	***	***
Clay		**	NS	NS	NS	*	NS	*	NS	***	***	***
Pct × Fert		***	***	***	***	*	***	**	NS	*	***	NS
Pct × Clay		NS	**	NS	NS	NS	NS	NS	NS	NS	***	**
Fert × Clay		***	*	*	***	NS	***	NS	NS	NS	**	NS
Pct × Fert × Clay		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zComplete control.

^yLSD used to compare clay treatments within a given fertilizer treatment (–P, –K, or complete) to the control medium. Pct × Fert interaction is significant.

^xLSD used to compare clay treatments at a percent level (10% or 30%) of a fertilizer treatment (–P, –K, or complete) to the control medium. Pct × Fert interaction is nonsignificant.

^wLSD used to compare clay treatments of a fertilizer treatment (–P, –K, or complete) at a percent level (10% or 30%) to the control medium. Pct × fert interaction is nonsignificant.

^vLSD used to compare brick chips means of both –P and complete fertilizer treatments with other treatment means.

^uFactorial treatment analysis of two calcined clays by 2% of mix by three fertilizers.

NS, *, **, *** Nonsignificant or significant at $P = 0.05, 0.01$ or 0.0001 , respectively.

Fig. 2. Mineral nutrient concentrations of unaltered bulk root medium solution during greenhouse Expt. 1 of media treated with precharged calcined clays, brick chips, and controls. (A and B) $\text{PO}_4\text{-P}$ ($\text{SE} = \pm 1.8$); (C and D) K ($\text{SE} = \pm 5.4$), and (E and F) pH of precharged and uncharged treatments, ($\text{SE} = \pm 0.1$); (■) complete control; (□) -P or -K fertilizer; (+) precharged attapulgite, 10% or 30% of mix, with -P or -K fertilizer; (●) precharged arcillite, 10% or 30% of mix, with -P or -K fertilizer; (◆) precharged brick chips, 30% of mix, with -P fertilizer; (▼) uncharged attapulgite, 10% or 30% of mix; (○) uncharged arcillite, 10% or 30% of mix; and (◇) = uncharged brick chips, 30% of mix. In all figures each symbol is based on three observations (two plants were used to obtain each observation).

Table 4. Physical properties characteristics of root medium formulations used in Expts. 1 and 2 as measured in a 10-cm-deep, 10-cm-round (0.05-L pot), plastic pot following the procedures of Niedziela and Nelson (1992).

Medium (v/v)	Bulk density (g cm^{-3})	Particle density (g cm^{-3})	Air-filled porosity	Container capacity (%)	Total porosity
Expt. 1					
7 peat : 3 perlite	0.17	0.96	11.7	68.0	79.7
7 peat : 2 perlite : 1 attapulgite	0.20	0.97	9.0	68.2	77.2
7 peat : 3 attapulgite	0.33	1.95	8.1	72.6	80.7
7 peat : 2 perlite : 1 arcillite	0.22	1.08	9.5	68.0	77.5
7 peat : 3 arcillite	0.37	2.09	7.6	72.2	79.8
LSD _{0.05}	0.03	0.45	3.3	3.6	NS
Expt. 2					
7 peat : 3 perlite	0.20	2.20	13.3	74.8	88.1
6.5 peat : 1.5 perlite : 2 attapulgite	0.25	2.33	13.5	73.1	86.6
6.5 peat : 1.5 perlite : 20 arcillite	0.27	2.50	16.7	69.2	85.9
6 peat : 1 perlite : 3 brick chips	0.39	1.90	12.8	64.6	77.4
LSD _{0.05}	0.06	NS	NS	4.5	6.3

^{NS}Nonsignificant.

tissue K levels (Table 3) of these plants were inadequate at both the midpoint and end of the crop, although concentrations were significantly higher in plants grown with 30% as compared to 10% of the precharged clay. The medium solution K levels indicated that K release from the precharged clays was substantial for the first 25 to 35 d of the cropping cycle (Fig. 2 C and D). By day 22, K release dropped below 10 mg L^{-1} for precharged arcillite at 10% of the medium; by day 29, it had dropped below this threshold for precharged attapulgite at 10% of the mix; and by day 43, K levels were below 10 mg L^{-1} for both precharged clays comprising 30% of the medium. These levels were inadequate to meet plant demands for optimal growth, as determined by plant appearance. Thus, the K from precharging the clays could provide some of the K needed during chrysanthemum production, but this source alone was inadequate to sustain plant needs.

Growth characteristics of plants grown in uncharged clays and brick chips were generally not significantly different from the complete control, except that dry weight of plants grown in 10% attapulgite was lower (Table 2). Medium solution $\text{PO}_4\text{-P}$ concentrations (Fig. 2A and B) were lower in the uncharged attapulgite treatments than the complete control. This suggested that the uncharged attapulgite removed PO_4 from solution until sorption sites were saturated, perhaps for as long as 57 d of the cropping cycle, during which time less P was available for uptake by the plant. Uncharged arcillite and brick chips had little effect on the $\text{PO}_4\text{-P}$ levels recovered in the bulk medium solution. Uncharged attapulgite at 30% of the mix was the only clay treatment which appeared to reduce K available for plant uptake by removing it from solution (Fig. 2 C and D).

GREENHOUSE EXPERIMENT 2. Growth of plants in 20% precharged attapulgite and arcillite and -P fertilizer was not significantly different than that of the complete control based on all five growth characteristics. Precharged brick chips resulted in less growth (except height) than the complete control (Table 5). Tissue analyses confirmed that P levels were optimal at both the midpoint and end of the crop for plants grown with a precharged clay. Phosphorus recovered in plants grown with precharged brick chips as their sole PO_4 source also met the minimum critical P levels, but was significantly less than in plants grown with 20% precharged clays and the complete control (Table 6). The medium solution $\text{PO}_4\text{-P}$ levels (Fig. 3A) were similar to those observed in Expt. 1 with levels for 20%

Table 5. Plant growth characteristics for shoots at end of the crop (day 67) of 'Sunny Mandalay' chrysanthemums grown with precharged calcined clays comprising 20% of the medium, brick chips comprising 30% of the medium, and a peat-based control medium (Expt. 2).

Source	Mix (%)	Ht (cm)	Width (cm)	Fresh wt (g)	Dry wt (g)	Rating ^z
Control medium						
Complete fertilizer ^y		22.3	38.5	144.7	16.1	10.0
–P fertilizer		14.7	17.2	13.7	3.3	2.0
Precharged clays						
Attapulgit	20	22.0	38.3	146.7	16.1	10.0
Arcillite	20	21.8	38.1	141.4	16.4	10.0
Brick chips	30	22.3	35.0	116.2	13.7	9.3
LSD _{0.05}		1.9	2.6	9.1	1.6	0.5

^zScale of 1 to 10 with 1 = death and 10 = optimum commercial growth.

^yComplete control.

Table 6. Mineral nutrient content (dry weight basis) of the youngest fully expanded leaves collected at midcrop (day 36) and of whole shoots at end of the crop (day 67) of 'Sunny Mandalay' chrysanthemums grown with precharged calcined clays comprising 20% of the medium, brick chips comprising 30% of the medium, and a peat-based control medium (Expt. 2).

Source	Mix (%)	Mineral										
		N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B
		(%)						(μg g ⁻¹)				
Midcrop												
Control medium												
Complete fertilizer ^z		4.94	0.64	3.88	0.91	0.56	---	69	503	383	15	---
–P fertilizer		3.29	0.10	3.93	0.47	0.27	---	59	487	410	17	---
Precharged clays												
Attapulgite	20	5.03	0.58	5.40	0.85	0.43	---	56	525	80	12	---
Arcillite	20	4.84	0.45	4.79	0.85	0.35	---	91	754	185	14	---
Brick chips	30	5.13	0.38	4.46	0.94	0.53	---	71	896	184	18	---
LSD _{0.05}		0.42	0.05	0.41	0.05	0.04		8	111	72	2	
End crop												
Control medium												
Complete fertilizer ^z		3.94	0.79	3.79	0.89	0.53	0.21	64	269	439	15	46
–P fertilizer		2.91	0.09	3.44	0.63	0.33	0.23	58	604	737	23	67
Precharged clays												
Attapulgite	20	4.21	0.46	4.65	1.04	0.46	0.25	72	277	121	15	48
Arcillite	20	3.86	0.31	4.13	0.95	0.41	0.35	72	326	306	16	53
Brick chips	30	3.49	0.23	4.28	1.01	0.50	0.31	76	380	329	22	57
LSD _{0.05}		0.35	0.06	0.38	0.08	0.05	0.05	NS	80	92	2	NS

^zComplete control.

^{NS}Nonsignificant.

precharged clays in Expt. 2 falling approximately between levels from Expt. 1 for 10% and 30% precharged clays. Late in the cropping cycle, PO₄-P levels in the root medium did not fall below 0.2 mg L⁻¹ for plants grown in precharged clays which comprised 20% of the medium. However, PO₄-P levels dropped below the critical level of 0.2 mg L⁻¹ by day 57 of the cropping cycle for plants grown with 30% precharged brick chips (Fig. 3A). Ideally, release of PO₄ from the test materials would not be so high during the first half of the cropping cycle, but instead, sustained at lower levels for the duration of crop production. Potassium levels in plants grown with precharged clays (Table 6) were significantly higher than in the complete control, which may be in part attributed to superoptimal release of K from the precharged clays early in the cropping cycle. This led to luxury consumption as observed in Expt. 1.

The pH of medium solution from plants grown with precharged clays and brick chips was again 1 to 2 units higher than in the control plants (Fig. 3B), similar to the results in Expt. 1 (Fig. 2E and F). This indicated that the differences in fertilizer NH₄: NO₃ ratio had little

effect on medium pH, compared to the effects of the test materials themselves. Similar increases in pH of soilless media were observed by Warren and Bilderback (1992) in an experiment with arcillite and by Carlile and Bedford (1988) in a study with waste from brick production.

In Expt. 1, 30% precharged clays did not result in growth similar to the complete control (Table 2), but they did in Expt. 2 at a volume of 20% of the mix. This result in Expt. 2 could be attributed to the more carefully controlled watering procedures which likely reduced leaching and/or increased aeration in the root medium due to the changes in media formulation.

A P budget showed that 36% (103 mg) of the applied PO₄ of the complete control treatment was lost in the leachate, whereas only 5.9% (36.1 mg) and 18.4% (21.6 mg) were lost from the precharged attapulgit and arcillite treatments, respectively (Table 7). The lesser amounts of PO₄ recovered by the plants grown with precharged clays compared to the complete control did not indicate inadequate PO₄. Instead, it was an indication of luxury consumption of PO₄ by

Fig. 3. Phosphate concentration and pH of unaltered bulk root medium solution during greenhouse Expt. 2 of root media treated with precharged calcined clays and brick chips and complete control. (A) $\text{PO}_4\text{-P}$ ($\text{SE} = \pm 1.3$) and (B) pH ($\text{SE} = \pm 0.1$); (■) complete control; (□) -P fertilizer; (+) = precharged attapulgite, 20% of mix; (●) precharged arcillite, 20% of mix; and (◆) precharged brick chips, 30% of mix. In all figures each symbol is based on three observations (two plants were used to obtain each observation).

the complete control. Substantial amounts of the PO_4 applied as precharged clays remained in pots at the end of the crop and were not used during crop production.

The use of precharged clays in soilless media can provide PO_4 to meet chrysanthemum needs during production. Their ability to successfully meet plant K needs was not demonstrated by this research. Brick chips supplied adequate PO_4 over the 10 week cropping cycle. The release of PO_4 over the course of the cropping cycle from the precharged clays was not ideal, with levels wastefully high early during production and decreasing to just above the minimum critical levels toward the end of production. However, these studies showed that a clay-based amendment can provide the capacity to retain and release PO_4 in a soilless container medium. Other clays or altered calcining processes may

provide greater facility for PO_4 and K retention and release as a basis for this alternative slow-release fertilizer.

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Table 7. Average proportion of added P recovered in the leachate in 'Sunny Mandalay' chrysanthemums, or estimated to remain in pots from treatments with precharged attapulgite, arcillite, or brick chips comprising 20% or 30% of the medium (v/v), and a peat-based control medium (Expt. 2).

Source	Mix (%)	Total P applied (mg/pot)	Plants			
			Leachate	Shoots	Estimated roots ^z	Estimated P remaining in pot ^y
Control medium						
Complete fertilizer ^x			36.5	45.0	11.2	7.2
		(280.9)	(102.6) ^w	(126.5)	(31.6)	(20.1)
–P fertilizer		(0)		(2.8)	(0.7)	
Precharged clays, –P fertilizer						
Attapulgite	20		5.9	12.1	3.0	78.9
		(612.7)	(36.1)	(74.4)	(18.6)	(483.6)
Arcillite	20		18.4	43.4	10.9	29.0
		(116.8)	(21.6)	(50.7)	(12.7)	(33.9)
Brick chips	30		10.5	26.0	6.5	57.0
		(119.2)	(12.5)	(31.0)	(7.7)	(68.0)
LSD _{0.05} ^v			7.6	3.8	1.0	7.2

^zLiberal estimation of P in roots was calculated by assuming that root mass was 25% of the shoot dry weight and P concentration in roots was the same as in shoot.

^yCalculated by subtracting P recovered in plants and leachate from the total applied.

^xComplete control.

^wNumbers in parentheses are mg P.

^vLSD calculated for percentage values.