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COMPARISON OF PHOSPHATE FERTILIZERS

Fertilizer Value of Calcined and Fused Phosphates on Typical Soils

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A greenhouse experiment was performed in order to compare four —200-mesh, single-step thermal process phosphates with triple superphosphate and phosphate rock as sources of phosphorus for alfalfa and rye grass on ten typical soils of the United States. Rhenania phosphate, Coronet phosphate, and phosphate rock–magnesium silicate glass had nutritive values about equal to that of superphosphate when applied to calcareous soils of the western United States, while fused tricalcium phosphate had a lower nutritive value. Response to phosphorus application was low on these soils. The furnace phosphates and superphosphate gave comparable results with alfalfa on the midwestern, southeastern, and Mississippi blackbelt soils; with rye grass, Rhenania phosphate gave a lower nutritive response than the other materials. Phosphate rock showed little or no response over the no-phosphorus treatment on all the soils.

PHOSPHATE FERTILIZERS manufactured by single-step thermal processes have received considerable attention for many years. This class of products consists of water-insoluble citrate-soluble phosphates, which, being alkaline in reaction, cause evolution of ammonia when they are placed in contact with ammonium salts and moisture. As these materials are not well suited, therefore, for general use in mixed fertilizers, their place in the fertilizer economy must be found largely in cropping programs that call for application of phosphate either alone or in conjunction with potash, for example, as may be required in the growing of legumes and sod crops.

Among the single-step thermal treatments that have been developed on a commercial scale are: (I) sintering or fusion of phosphate rock with a suitable complement of silica in the presence of water vapor, whereby nearly all the fluorine in the rock is evolved, as in the cristobalite process (*25*) formerly utilized by the Coronet Phosphate Co. to produce a feed supplement, or in the fusion process (*10*) used by the Tennessee Valley Authority; (II) fusion of phosphate rock with magnesium silicate (*24*), as formerly done on the West Coast by the Permanente Metals Corp. (*4*) and Manganese Products, Inc. (*14*); and (III) calcination of phosphate rock with alkali salts—for example, with sodium carbonate as in the Rhenania process operated in Germany (*9*).

During the past few years considerable experimentation with production and use of Rhenania-type phosphate of the kind made in Germany has been conducted in the Rocky Mountain region. This product has shown favorable crop response on calcareous soils (*20*), even as good as the water-soluble phosphates, which are generally preferred for use on these soils (*2*). On the other hand, defluorinated phosphate rock has been reported to be relatively ineffective on calcareous soils (*5–7*, *13*), as has also its principal constituent, α-tricalcium phosphate (*17*). The marked differences among observed crop responses to these phosphates suggested the need for an experiment that would permit a direct comparison of the several types of materials from single-step thermal processes on typical soils representing several of the great soil groups of the United States. Such an experiment was conducted in the greenhouse and results are presented here.

Table I. Composition of Phosphate Materials

Phosphorus Carrier	Sample No.	Mesh	P_2O_5, % Total	P_2O_5, % Available	P_2O_5, % Water-soluble	CaO, %	Na_2O (MgO), %	F, %
Triple superphosphate	3032	−28	50.0	48.8	44.0	22.5	...	1.6
Rhenania phosphate	3025	−200	25.8	20.1	0.3	37.4	16.6	2.9
Coronet phosphate	3022	−200	38.8	36.0	0.1	49.1	5.5	0.03
Fused tricalcium phosphate	3031	−200	28.0	23.4	0.1	39.8	...	0.3
Phosphate rock–magnesium silicate glass	2497	−200	20.4	16.5	0.1	32.4	(17.1)	1.7
Phosphate rock	2968	−200	33.7	3.4	0.03	48	...	3.7

Phosphate Materials

The test phosphate materials were commercial preparations of four products: Rhenania phosphate, Coronet phosphate, fused tricalcium phosphate, and phosphate rock–magnesium silicate glass (Table I). The sample of Rhenania phosphate was from material made in Germany since World War II. The Coronet phosphate, a defluorinated phosphate rock, was from material produced in late 1951 by the Coronet Phosphate Co., Plant City, Fla., and marketed as a feed supplement. A silicocarnotitelike compound appears to be the dominant phosphate constituent in both materials (*3*).

Table II. Characteristics of Soils Prior to Application of Lime and Fertilizer[a]

Geographic Region in U. S.	Great Soil Group	Soil Type	Sample No.	pH	Exchangeable Cations, Meq./100 Grams Soil: Ca	Mg	K	Na	H	Sum	Base Saturation, %	Organic Carbon, %	Lb. P_2O_5/Acre, Soluble in 0.05 M $NaHCO_3$[b]	Lb. P_2O_5/Acre, Soluble in 0.002 N H_2SO_4[c]
West	Chestnut	Millville silt loam	52382	8.3	22.5	10.3	0.7	0.3	0.0	33.8	100	1.69	50	..
	Brown	Nunn silty clay[d]	52379	7.8	26.2	5.7	1.1	0.4	1.3	34.7	96	1.47	41	..
	Brown	Fort Collins sandy clay loam[d]	52380	8.0	26.2	2.2	0.9	0.3	0.6	30.2	98	1.21	62	..
Midwest	Prairie or Brunigra	Carrington loam	52381	5.1	11.4	1.7	0.1	0.1	14.8	28.1	47	3.84	29	40
	Gray brown Podzolic	Miami fine sandy loam	52377	6.6	8.1	0.4	<0.1	0.1	4.3	12.9	67	1.58	22	47
Southeast	Reddish brown Latosol	Davidson silty clay loam	52374	5.4	3.9	0.8	0.4	0.1	12.9	18.1	29	1.83	24	14
	Red yellow Podzolic	Orangeburg sandy loam												
	Red yellow Pod-	Cecil sandy loam	52375	4.8	0.8	<0.1	0.2	0.3	2.4	3.7	35	0.97	69	58
	zolic		52376	6.1	1.5	1.1	0.1	0.2	3.2	6.1	48	0.58	10	19
	Red yellow Podzolic	Evesboro loamy sand	52383	4.8	0.9	0.1	0.1	0.2	1.9	3.2	41	0.53	22	17
Mississippi blackland	Grumusol	Hunt clay	52378	7.1	33.9	0.4	0.3	0.2	4.4	39.2	89	2.30	22	50

[a] Soil type designation and all chemical analyses except phosphorus by Soil Survey Laboratory, Soil Conservation Service, Beltsville, Md.
[b] Determined by method of Olsen and others (*16*).
[c] Determined by modified Truog method (*18*).
[d] Laboratory textural designation. Field texture not determined.

Table III. Oven-Dry Weight of First Alfalfa Cutting

(Grams per pot)

Treatment: Phosphorus carrier	Applied P_2O_5 lb./acre	Western Soils: Millville	Nunn	Ft. Collins	Group mean	Midwestern Soils: Carrington	Miami	Group mean	Southeastern Soils: Orangeburg	Cecil	Evesboro	Group mean	Mississippi Blackbelt Soil, Hunt
Triple superphosphate	50	4.37	3.98	4.21	4.18	3.01	0.91	1.96	2.07	2.33	1.95	2.12	2.01
	150	4.30	4.33	4.09	4.24	3.20	1.86	2.53	2.63	2.43	2.81	2.62	2.74
Mean		4.34	4.15	4.15	4.21	3.11	1.38	2.25	2.35	2.38	2.38	2.37	2.38
Rhenania-type phosphate	50	4.07	3.99	3.73	3.93	2.43	0.53	1.48	2.01	2.19	1.87	2.02	2.39
	150	4.88	4.24	4.61	4.58	3.77	1.66	2.93	2.53	2.44	2.27	2.41	2.80
Mean		4.48	4.11	4.17	4.26	3.10	1.31	2.20	2.27	2.32	2.07	2.22	2.59
Coronet phosphate	50	4.07	4.05	3.57	3.90	3.18	1.29	2.23	1.98	1.92	2.01	1.97	2.44
	150	4.36	4.08	4.49	4.31	3.43	1.80	2.62	2.41	2.51	2.30	2.41	2.61
Mean		4.21	4.07	4.03	4.11	3.31	1.54	2.43	2.20	2.22	2.16	2.19	2.53
Fused tricalcium phosphate	50	3.53	3.89	3.89	3.77	2.28	1.03	1.66	2.06	2.04	1.67	1.92	1.91
	150	3.85	4.10	4.09	4.01	3.30	1.94	2.62	2.38	2.69	2.26	2.44	2.49
Mean		3.69	4.00	3.99	3.89	2.79	1.48	2.14	2.22	2.36	1.96	2.18	2.20
Phosphate rock—magnesium silicate glass	50	4.05	3.88	3.72	3.88	2.30	1.09	1.69	2.19	2.28	1.62	2.03	2.57
	150	4.42	4.38	4.34	4.38	2.82	1.76	2.29	2.10	2.37	2.14	2.20	2.85
Mean		4.23	4.13	4.03	4.13	2.56	1.43	1.99	2.15	2.33	1.88	2.12	2.71
Phosphate rock	50	3.75	3.42	3.65	3.61	1.53	0.45	0.99	1.86	0.93	1.03	1.27	1.47
	150	3.62	3.73	4.27	3.87	2.18	0.51	1.34	1.83	1.08	1.17	1.36	1.54
Mean		3.69	3.58	3.96	3.74	1.85	0.48	1.17	1.85	1.00	1.10	1.32	1.51
No phosphorus		3.72	3.65	3.79	3.72	1.25	0.41	0.83	1.62	0.68	1.06	1.12	1.50

Least Significant Differences (Grams) for Comparisons	Level of Significance: 5%	1%
Treatments within single soil	0.54	0.71
Group means of treatments		
Within two-soil combination	0.38	0.50
Within three-soil combination	0.31	0.41
Means of carriers and/or no phosphorus within single soil	0.38	0.50
Group means of carriers and/or no phosphorus		
Within two-soil combination	0.31	0.41
Within three-soil combination	0.22	0.29

Table IV. Oven-Dry Weight of Three Alfalfa Cuttings

(Grams per pot)

Treatment		Western Soils				Midwestern Soils			Southeastern Soils				Mississippi Blackbelt Soil, Hunt
Phosphorus carrier	Applied P_2O_5, lb./acre	Millville	Nunn	Ft. Collins	Group mean	Carrington	Miami	Group mean	Orangeburg	Cecil	Evesboro	Group mean	
Triple superphosphate	50	11.09	11.20	11.17	11.15	7.90	5.08	6.49	4.12	5.91	6.25	5.43	6.58
	150	11.38	11.29	11.01	11.23	8.92	6.93	7.93	6.20	6.30	7.82	6.78	8.38
Mean		11.24	11.25	11.09	11.19	8.41	6.01	7.21	5.16	6.11	7.04	6.11	7.48
Rhenania-type phosphate	50	11.60	11.13	10.51	11.08	7.13	4.84	5.99	4.89	5.61	5.94	5.48	7.18
	150	11.80	11.51	11.59	11.63	8.98	6.93	7.93	6.02	6.20	7.12	6.45	8.62
Mean		11.70	11.32	11.04	11.36	8.06	5.89	6.96	5.46	5.91	6.53	5.97	7.90
Coronet phosphate	50	10.55	10.52	10.63	10.57	8.20	6.02	7.11	4.63	5.61	6.38	5.54	6.89
	150	12.16	10.91	12.00	11.69	8.64	6.48	7.56	5.60	6.75	7.18	6.51	8.03
Mean		11.36	10.72	11.32	11.13	8.42	6.25	7.34	5.12	6.18	6.78	6.03	7.46
Fused tricalcium phosphate	50	10.07	10.68	11.20	10.65	6.58	5.39	5.98	5.28	5.49	5.79	5.52	6.82
	150	10.99	10.51	10.99	10.83	8.41	7.23	7.82	5.79	6.52	7.33	6.55	7.51
Mean		10.53	10.60	11.10	10.74	7.50	6.31	6.90	5.54	6.01	6.56	6.04	7.17
Phosphate rock–magnesium silicate glass	50	10.93	10.28	10.80	10.67	7.12	5.60	6.36	5.27	5.63	5.86	5.59	7.06
	150	11.23	11.44	11.72	11.46	7.97	6.76	7.36	4.73	6.31	6.95	6.00	7.92
Mean		11.08	10.86	11.26	11.07	7.55	6.18	6.86	5.00	5.97	6.41	5.80	7.49
Phosphate rock	50	10.05	8.87	10.83	9.92	6.11	4.23	5.17	4.95	3.58	4.55	4.36	5.18
	150	9.81	9.27	11.04	10.04	6.83	4.53	5.68	4.74	3.85	4.77	4.45	5.10
Mean		9.93	9.07	10.94	9.96	6.47	4.38	5.43	4.85	3.72	4.62	4.41	5.14
No phosphorus		10.11	9.47	10.85	10.14	6.06	4.03	5.04	4.53	2.77	4.41	3.90	4.55

Least Significant Differences (Grams) for Comparisons	Level of Significance 5%	1%
Treatments within single soil	1.03	1.36
Group means of treatments		
Within two-soil combination	0.73	0.96
Within three-soil combination	0.59	0.78
Means of carriers and/or no phosphorus within single soil	0.73	0.96
Group means of carriers and/or no phosphorus		
Within two-soil combination	0.59	0.78
Within three-soil combination	0.42	0.55

The fused tricalcium phosphate, produced by the Tennessee Valley Authority, Columbia, Tenn., was made by defluorinating a melt of phosphate rock containing a suitable proportion of silica and then quenching it in water. The product consisted of α-tricalcium phosphate crystals and variable, though appreciable, quantities of phosphate-bearing glass. The phosphate rock–magnesium silicate glass, made about 1946 by the Permanente Metals Corp., Permanente, Calif., by fusing a proportioned mixture of Idaho phosphate rock and calcined serpentine, was substantially an all-glass product; this type of material is not manufactured in the United States at present.

Triple superphosphate and phosphate rock, which represent the extremes of the range of phosphorus solubilities, were included as reference standards. The superphosphate was made from Florida land pebble phosphate. The phosphate rock was a Florida land pebble from material currently being used in a series of long-time field experiments by the North Central Regional Phosphorus Work Group. For use in the experiments, the thermal process phosphates and phosphate rock, as received, were reground to pass the 200-mesh sieve. The triple superphosphate was ground to pass the 28-mesh sieve.

Soils

Soils representing several of the great soil groups of the United States were used. The characteristics of the soils prior to application of lime and fertilizer are shown in Table II, in which the soils are grouped according to geographic regions. The Hunt clay, collected at the Mississippi Blackbelt Branch Experiment Station, is characteristic of the blackbelt extending through central Alabama and northeastern Mississippi as well as the blackland prairies of central Texas and southern Oklahoma. Oakes and Thorp (*15*) have proposed that the great soil group name of the blackland soils be changed from Rendzina to Grumusol. Smith and Reicken (*21*) have proposed that the name of prairie soils be changed to Brunigra.

The western soils (Table II) showed high values for ammonium acetate–extractable calcium, percentage base saturation, and pH, whereas the midwestern soils had moderately high values for these properties and also for extractable phosphorus pentoxide content. Although the Carrington and Miami soils are found in the same geographic region, the former, developed under grass, had a somewhat greater content of ammonium acetate–extractable calcium and other bases than the latter, which was developed under forest vegetation. The percentage base saturation, pH, and extractable phosphorus pentoxide content of the soils of the southeast were generally low. An exception was the Orangeburg soil with a relatively high extractable phosphorus pentoxide content. The Hunt soil, developed under grass, had a high content of ammonium acetate–extractable calcium and other bases and was nearly neutral.

Procedure

Ranger alfalfa and perennial rye grass were grown on nine of the ten soils. Davidson soil was not used for growing alfalfa and Orangeburg soil was not used for rye grass. Enamel-lined No. 10 metal cans were used as containers.

The Orangeburg, Cecil, Evesboro, Davidson, and Carrington soils received applications of calcium hydroxide equivalent to 1680, 630, 1500, 3360, and 5250

Table V. Phosphorus Uptake by First Alfalfa Cutting

(Milligrams P_2O_5 per pot)

Treatment: Phosphorus carrier	Treatment: Applied P_2O_5, lb./acre	Western Soils: Millville	Western Soils: Nunn	Western Soils: Ft. Collins	Western Soils: Group mean	Midwestern Soils: Carrington	Midwestern Soils: Miami	Midwestern Soils: Group mean	Southeastern Soils: Orangeburg	Southeastern Soils: Cecil	Southeastern Soils: Evesboro	Southeastern Soils: Group mean	Mississippi Blackbelt Soil, Hunt
Triple superphosphate	50	23.0	19.9	23.4	21.9	16.0	5.1	10.5	12.5	10.4	11.9	11.6	9.1
	150	25.8	24.6	24.2	24.9	19.9	10.7	15.3	15.7	12.8	17.6	15.4	17.0
Mean		24.4	22.2	23.8	23.4	17.9	7.9	12.9	14.1	11.6	14.8	13.5	13.5
Rhenania-type phosphate	50	21.7	18.0	21.9	20.5	12.4	3.4	7.8	11.3	10.7	11.0	11.0	10.0
	150	31.0	25.9	26.3	27.7	22.7	12.5	17.6	15.4	13.0	13.4	13.0	12.6
Mean		26.3	21.9	24.0	24.1	17.5	7.9	12.7	13.4	11.8	12.2	12.5	11.3
Coronet phosphate	50	20.9	19.6	16.7	19.1	18.2	8.1	13.2	11.8	8.6	11.0	10.5	12.1
	150	23.6	24.9	24.5	24.3	20.2	10.7	15.5	13.6	13.3	14.5	13.8	15.8
Mean		22.2	22.3	20.6	21.7	19.2	9.4	14.3	12.7	11.0	12.7	12.1	14.0
Fused tricalcium phosphate	50	17.1	17.4	18.0	17.5	10.5	6.0	8.2	12.0	8.9	8.9	9.9	8.2
	150	19.6	20.4	21.4	20.4	18.7	10.9	14.8	15.4	14.2	13.0	14.2	13.7
Mean		18.3	18.9	19.7	19.0	14.6	8.4	11.5	13.7	11.6	11.0	12.1	11.0
Phosphate rock–magnesium silicate glass	50	21.2	20.1	22.2	21.2	12.2	6.7	9.5	12.9	10.0	8.5	10.4	13.8
	150	25.9	23.9	24.4	24.7	15.2	10.0	12.6	13.1	12.0	13.1	12.7	16.1
Mean		23.5	22.0	23.3	23.0	13.7	8.4	11.0	13.0	11.0	10.8	11.6	14.9
Phosphate rock	50	16.4	15.6	17.5	16.5	7.6	2.9	5.2	10.3	1.9	5.8	6.0	5.8
	150	14.4	17.8	22.0	18.1	12.0	3.4	7.7	10.5	4.0	6.8	7.1	4.9
Mean		15.4	16.7	19.8	17.5	9.8	3.1	6.5	10.4	3.0	6.3	6.5	5.4
No phosphorus		16.8	16.3	19.6	17.6	6.3	2.5	4.4	8.7	2.9	5.5	5.6	5.1

Least Significant Differences (Mg.) for Comparisons	Level of Significance: 5%	Level of Significance: 1%
Treatments within single soil	3.7	4.9
Group means of treatments		
Within two-soil combination	2.6	3.5
Within three-soil combination	2.2	2.8
Means of carriers and/or no phosphorus within single soil	2.6	3.5
Group means of carriers and/or no phosphorus		
Within two-soil combination	2.2	2.8
Within three-soil combination	1.5	2.0

pounds of calcium carbonate per acre, respectively, 1 week before seeding. Laboratory tests had indicated these amounts to be adequate to raise the pH to 6.5.

All pots were given a basal treatment of nitrogen and potash. The pots for alfalfa received 50 pounds of nitrogen per acre as ammonium sulfate and 150 pounds of potassium oxide as potassium chloride; the pots for rye grass received 100 pounds of nitrogen as ammonium sulfate and 150 pounds of potassium oxide as potassium chloride.

The lime, nitrogen, and potash were mixed throughout the soil. Magnesium sulfate in solution was applied to all except the western soils at the rate of 25 pounds of magnesia per acre. Borax and manganese sulfate, both in solution, were applied to the midwestern and southeastern soils at rates of 10 and 30 pounds per acre, respectively.

The six phosphorus carriers were mixed throughout the soil at rates of 50 and 150 pounds of total phosphorus pentoxide per acre. Six no-phosphorus treatments were used for each crop on each soil. A randomized block design with split plots for crops and soils was used in three replications.

Both crops were planted on April 11. The first, second, and third cuttings of alfalfa were harvested at 55, 87, and 118 days, respectively, and the corresponding cuttings of rye grass at 46, 73, and 110 days from time of planting.

Total phosphorus was determined on the plant material of the first cutting. Analyses of variance were performed on the oven-dry weights of the first cutting, phosphorus uptakes of the first cutting, and the sum of oven-dry weights for the three cuttings.

Results

The yield for the first cutting, combined yield of the three cuttings, and phosphorus uptake for the first cutting of alfalfa are summarized in Tables III, IV, and V, respectively. Those for rye grass are summarized in Tables VI, VII, and VIII. The arrangement permits comparisons between materials and applications by single soils or by geographical groupings of the soils. Of the southeastern soils, Orangeburg was used to grow only alfalfa, while Davidson was used to grow only rye grass. Least significant differences requisite for valid comparisons are given at the bottom of each table.

Crop Response to Reference Materials

The phosphate rock showed little or no response over the no-phosphorus treatment (Tables III to VIII). The instances of significant response are alfalfa yield and phosphorus uptake (first cutting) on the Carrington soil, yield (three cuttings) on the Cecil soil, and rye grass yield (first cutting) on the Evesboro soil. Significant differences between the amounts of rock applied were also shown for the Carrington and Cecil soils. The paucity of response is no surprise, as the amounts of rock applied were small in comparison with the rates customarily recommended.

The superphosphate, on the other hand, showed responses over the no-phosphorus treatment with both crops on all of the soils, and in most instances the response was highly significant. Significance was not attained in only four cases—namely, both alfalfa yields and one rye grass yield (three cuttings) on the Fort Collins soil and the three-harvest alfalfa yield on the Orangeburg soil. Apart from the results for alfalfa on the three western soils, both yields and uptakes were generally greater with a phosphorus pentoxide application of 150 pounds per acre than with 50 pounds.

Performance of Furnace Phosphates

The furnace phosphates as a group gave highly significant responses over the no-phosphorus treatment with both crops on all geographical groupings of the soils (Tables III to VIII). Only fused tricalcium phosphate with alfalfa on western soils (first cutting) failed to show significance. Responses on individual soils parallel those shown for the soil groups, except in the case of the Fort Collins soil, which did not respond to phosphorus fertilization.

Crop yields and phosphorus uptakes, for the experiment as a whole, were significantly greater when the materials were applied at the rate of 150 pounds of phosphorus pentoxide per acre than at 50 pounds. Exceptions, which may be noted from the tables, occurred most often on the western soils.

The relative efficiency of the furnace-made phosphates and the superphosphate was markedly influenced by both crop and soil. The performance of the materials according to their ability to produce three-cutting yields of each crop on soils of the four geographical regions is summarized in Table IX. The Roman numerals denote the descending order of observed crop response. Referring only to comparisons showing yields significantly different from those with superphosphate, the phosphate rock–magnesium silicate glass was superior to superphosphate for rye grass on western soils; Rhenania phosphate was an inferior source for rye grass on midwestern, southeastern, and Mississippi blackbelt soils; and fused tricalcium phosphate was an inferior source for alfalfa and rye grass on western soils.

Results Related to Previous Findings

The conclusions reached in previous investigations with materials similar to some of those used in this experiment are generally compatible with the results presented here. The observed equivalence of −200-mesh Rhenania phosphate and superphosphate with alfalfa on all soil groups and rye grass on western soils is in agreement with earlier findings. These include the field experiments of Schmehl and Brenes (*20*) with sugar beets, barley, and alfalfa on calcareous soils; Hofmann and others (*12*) with barley, rape, potatoes, wheat, and rye on German soils of a wide pH range; and pot experiments of Ris and Van der Paauw (*19*) with rye and rye grass on limed soils. Furthermore, the significantly lower value found in the present work for this material with rye grass on the midwestern, southeastern, and Mississippi blackbelt soils parallels the results obtained by Ris and Van der Paauw (*19*) with rye and rye grass on unlimed peat, acid sand, and neutral clay soils of Europe.

Coronet phosphate of the type used in this study has not, as far as the authors are aware, been used in other crop-response experiments.

The low nutritive value found for fused tricalcium phosphate on calcareous soils has been observed repeatedly by other workers (*5–7*, *13*). Also the statistical equivalence of this phosphate (−200-mesh) and superphosphate with alfalfa and rye grass on midwestern soils is in line with the conclusions of Alway and Nesom (*1*) from field experiments with alfalfa on slightly acid Clarion clay loam and also the findings of Stanford and Nelson (*22*) in field experiments with alfalfa and oats on Clarion loam and Webster silty clay loam soils. Similarly, its favorable showing with alfalfa and rye grass on southeastern soils follows closely the findings reported by Jacob and Ross (*13*) from greenhouse experiments with German millet and sudan grass on six acid soils, and also those of Volk (*23*) with sorghum and oats on Hartsells fine sandy loam, Norfolk sandy loam, and Cecil clay.

Table VI. Oven-Dry Weight of First Rye Grass Cutting

(Grams per pot)

Treatment: Phosphorus carrier	Applied P_2O_5, lb./acre	Western Soils: Millville	Nunn	Ft. Collins	Group mean	Midwestern Soils: Carrington	Miami	Group mean	Southeastern Soils: Davidson	Cecil	Evesboro	Group mean	Mississippi Blackbelt Soil, Hunt
Triple superphosphate	50	2.18	1.86	2.06	2.03	1.45	2.05	1.75	1.54	3.10	3.68	2.77	2.34
	150	2.78	2.47	2.55	2.60	2.61	3.16	2.89	3.49	4.21	4.55	4.08	3.04
Mean		2.48	2.16	2.30	2.32	2.03	2.61	2.32	2.52	3.65	4.11	3.42	2.69
Rhenania-type phosphate	50	2.09	2.13	2.04	2.09	1.44	1.45	1.45	0.93	2.45	3.60	2.33	1.88
	150	2.84	2.62	2.54	2.66	2.06	2.63	2.35	2.30	3.75	4.81	3.62	2.99
Mean		2.46	2.37	2.29	2.37	1.75	2.04	1.90	1.62	3.10	4.20	2.97	2.44
Coronet phosphate	50	1.91	1.93	1.71	1.85	1.48	2.31	1.89	1.32	3.15	3.64	2.70	2.44
	150	2.54	2.35	2.88	2.59	2.61	2.84	2.72	3.42	4.36	5.07	4.28	3.25
Mean		2.23	2.14	2.30	2.22	2.04	2.57	2.30	2.37	3.75	4.35	3.49	2.84
Fused tricalcium phosphate	50	1.68	1.59	1.98	1.75	1.42	1.71	1.57	1.45	3.63	3.82	2.97	2.64
	150	2.03	1.97	2.35	2.12	2.44	3.45	2.94	3.28	4.32	4.94	4.18	3.29
Mean		1.85	1.78	2.17	1.93	1.93	2.58	2.26	2.36	3.98	4.38	3.57	2.97
Phosphate rock–magnesium silicate glass	50	2.27	2.34	2.23	2.28	1.32	1.95	1.64	1.24	2.28	4.05	2.52	2.23
	150	3.53	3.17	2.34	3.01	2.30	3.18	2.74	3.29	4.39	5.10	4.26	3.46
Mean		2.90	2.76	2.29	2.65	1.81	2.57	2.19	2.26	3.33	4.58	3.39	2.84
Phosphate rock	50	1.47	1.26	1.72	1.48	0.61	0.66	0.63	0.15	0.87	1.34	0.79	1.00
	150	1.55	1.41	1.94	1.63	0.61	0.62	0.62	0.21	1.26	1.48	0.98	1.05
Mean		1.51	1.34	1.83	1.56	0.61	0.64	0.62	0.18	1.07	1.41	0.89	1.03
No phosphorus		1.37	1.22	1.83	1.48	0.55	0.73	0.64	0.22	0.90	0.95	0.69	0.82

Least Significant Differences (Grams) for Comparisons	Level of Significance: 5%	1%
Treatments within single soil	0.48	0.63
Group means of treatments		
Within two-soil combination	0.34	0.45
Within three-soil combination	0.27	0.36
Means of carriers and/or no phosphorus within single soil	0.34	0.45
Group means of carriers and/or no phosphorus		
Within two-soil combination	0.27	0.36
Within three-soil combination	0.19	0.26

According to Winterberg (*26*) this material was notably less effective than superphosphate on southeastern soils; but since his material was probably −40-mesh, the unfavorable showing is attributed, at least in part, to the coarseness of the test sample.

The superiority of −200-mesh phosphate rock–magnesium silicate glass, even over superphosphate, with rye grass on the western group of soils comes as a surprise, because earlier tests (*11*) with millet on a calcareous soil were generally unfavorable to −35- to −300-mesh preparations of this material. Contrariwise, in previous work (*11*) the −100-mesh was significantly superior to triple superphosphate with millet on a Nunn soil, whereas in the present study it was not significantly different from superphosphate on the midwestern soils. The favorable showing of the glass with rye grass on the southeastern soils parallels previous results (*11*) with millet on Evesboro soil. Its inferiority to superphosphate with alfalfa on this group of soils was not anticipated by published results.

Baker (*2*) indicated that the water-soluble phosphate fertilizers give the best results on the calcareous soils of the western United States. The results with the −200-mesh Rhenania phosphate, phosphate rock–magnesium silicate glass, and Coronet phosphate, which have very low water solubility and yet show nutritive values approximately equal to those of superphosphate, indicate that water solubility is not the only criterion for selection of phosphorus carriers for these soils. The presence of sodium or magnesium in these carriers may be partially responsible for their high nutritive values as compared to the fused tricalcium phosphate, which is primarily a calcium phosphate.

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Table VII. Oven-Dry Weight of Three Rye Grass Cuttings

(Grams per pot)

Treatment		Western Soils				Midwestern Soils			Southeastern Soils				Mississippi Blackbelt
Phosphorus carrier	Applied P_2O_5, lb./acre	Millville	Nunn	Ft. Collins	Group mean	Carrington	Miami	Group mean	Davidson	Cecil	Evesboro	Group mean	Soil, Hunt
Triple superphosphate	50	8.01	6.69	6.85	7.18	5.61	6.76	6.19	6.08	6.49	7.56	6.71	5.34
	150	8.91	7.74	6.94	7.86	6.87	8.30	7.86	8.24	7.59	8.11	7.98	7.02
Mean		8.46	7.22	6.90	7.52	6.24	7.53	7.03	7.16	7.04	7.84	7.35	6.18
Rhenania-type phosphate	50	7.96	6.82	6.68	7.15	5.35	6.05	5.70	4.49	6.52	6.78	5.93	4.99
	150	8.89	7.93	7.03	7.92	6.57	7.68	7.12	7.44	7.31	8.10	7.62	5.77
Mean		8.43	7.38	6.93	7.54	5.96	6.87	6.41	5.97	6.92	7.44	6.78	5.38
Coronet phosphate	50	7.42	6.67	6.82	6.97	4.89	7.18	6.04	5.51	6.66	7.34	6.50	5.18
	150	7.85	7.64	7.49	7.66	7.24	8.11	7.67	7.43	7.57	9.06	8.02	5.98
Mean		7.64	7.16	7.16	7.32	6.07	7.65	6.85	6.47	7.12	8.20	7.26	5.58
Fused tricalcium phosphate	50	7.08	5.77	6.74	6.53	5.19	6.33	5.76	6.02	7.56	7.43	7.00	5.69
	150	7.55	7.01	7.27	7.28	7.23	8.47	7.85	7.20	7.25	8.31	7.59	6.40
Mean		7.32	6.39	7.01	6.91	6.21	7.40	6.82	6.61	7.41	7.87	7.30	6.05
Phosphate rock–magnesium silicate glass	50	8.13	7.46	7.36	7.65	4.60	6.52	5.56	5.23	6.44	7.74	6.55	5.20
	150	9.79	8.36	7.35	8.50	6.60	8.17	7.38	8.59	7.79	8.98	8.45	6.34
Mean		8.96	7.91	7.36	8.08	5.60	7.35	6.87	6.91	7.12	8.41	7.50	5.82
Phosphate rock	50	6.36	5.43	6.59	6.12	3.51	4.65	4.08	2.43	4.73	5.66	4.27	3.40
	150	6.61	4.78	6.99	6.14	3.30	3.95	3.63	2.47	5.21	5.95	4.54	3.87
Mean		6.49	5.11	6.79	6.13	3.41	4.30	3.86	2.45	4.97	5.81	4.42	3.64
No phosphorus		6.12	5.32	6.49	5.92	3.21	4.24	3.73	2.01	4.74	4.96	3.90	3.05

Least Significant Differences (Grams) for Comparisons	Level of Significance 5%	1%
Treatments within single soil	1.02	1.34
Group means of treatments		
Within two-soil combination	0.72	0.95
Within three-soil combination	0.59	0.78
Means of carriers and/or no phosphorus within single soil	0.72	0.95
Group means of carriers and/or no phosphorus		
Within two-soil combination	0.59	0.78
Within three-soil combination	0.42	0.55

Table VIII. Phosphorus Uptake by First Rye Grass Cutting

(Milligrams P_2O_5 per pot)

Treatment		Western Soils				Midwestern Soils			Southeastern Soils				Mississippi Blackbelt Soil,
Phosphorus carrier	Applied P_2O_5, lb./acre	Millville	Nunn	Ft. Collins	Group mean	Carrington	Miami	Group mean	Davidson	Cecil	Evesboro	Group mean	Hunt
Triple superphosphate	50	11.5	10.8	11.9	11.4	7.5	10.0	8.7	5.0	14.4	20.5	13.3	10.5
	150	16.2	18.2	16.8	17.1	14.6	18.7	16.7	12.6	18.3	40.6	25.0	21.0
Mean		13.8	14.5	14.3	14.2	11.1	14.4	12.7	8.8	16.3	30.6	19.1	15.8
Rhenania-type phosphate	50	11.5	11.8	13.3	12.2	6.9	6.7	6.8	2.3	10.8	19.3	10.9	6.8
	150	18.0	18.1	17.8	18.0	11.2	15.1	13.1	9.3	11.4	39.2	23.3	14.2
Mean		14.7	14.9	15.5	15.1	9.0	10.9	10.0	5.8	11.1	29.3	17.1	10.5
Coronet phosphate	50	11.7	11.2	10.1	11.0	6.6	11.5	9.0	3.8	12.7	18.4	11.6	9.5
	150	15.9	13.6	16.0	15.2	11.1	17.5	14.3	12.7	25.7	43.5	27.4	18.3
Mean		13.8	12.4	13.0	13.1	8.9	14.5	11.7	8.2	19.2	31.0	19.5	13.9
Fused tricalcium phosphate	50	9.3	9.4	10.6	9.8	7.4	9.1	8.2	5.0	15.0	19.5	13.1	9.6
	150	11.0	11.3	14.0	12.1	12.2	21.1	16.6	10.1	25.2	39.4	24.9	17.1
Mean		10.2	10.3	12.3	10.9	9.8	15.1	12.4	7.5	20.1	29.5	19.0	13.3
Phosphate rock–	50												
magnesium sili-	150	13.5	13.4	13.4	13.4	5.7	9.4	7.5	3.6	9.6	21.3	11.5	9.9
cate glass		20.8	21.2	14.6	18.8	11.3	18.3	14.8	12.0	24.8	49.8	30.0	19.2
Mean		17.1	17.3	14.0	16.1	8.5	13.9	11.2	7.8	17.2	35.6	20.8	14.6
Phosphate rock	50	7.4	6.7	9.2	7.8	2.6	2.6	2.6	0.4	2.7	5.4	2.8	2.6
	150	8.0	7.1	11.2	8.8	2.7	2.7	2.7	0.6	3.1	5.5	3.1	2.9
Mean		7.7	6.9	10.2	8.3	2.6	2.7	2.7	0.5	2.9	5.4	2.9	2.8
No phosphorus		7.2	6.3	9.9	7.8	2.4	3.2	2.8	0.5	2.7	3.6	2.3	2.5

Least Significant Differences (Mg.) for Comparisons	Level of Significance 5%	1%
Treatments within single soil	2.1	2.8
Group means of treatments		
Within two-soil combination	1.5	2.0
Within three-soil combination	1.2	1.6
Means of carriers and/or no phosphorus within single soil	1.5	2.0
Group means of carriers and/or no phosphorus		
Within two-soil combination	1.2	1.6
Within three-soil combination	0.9	1.1

Table IX. Relative Performance of Superphosphate and Furnace Product Phosphates for Three-Cutting Yields of Two Crops on Soils of Four Geographical Regions

		Origin of Soils by Geographic Region in U. S.			
Phosphorus carrier	Crop	West	Midwest	Southeast	Mississippi blackbelt
Superphosphate	Alfalfa	II	II	I	III
	Rye grass	III	I	II	I
Rhenania phosphate	Alfalfa	I	III	IV	I
	Rye grass	II	V[a]	V[a]	V[a]
Coronet phosphate	Alfalfa	III	I	III	IV
	Rye grass	IV	III	IV	IV
Fused tricalcium phosphate	Alfalfa	V[a]	IV	II	V
	Rye grass	V[a]	IV	III	II
Phosphate rock–magnesium silicate glass	Alfalfa	IV	V	V	II
	Rye grass	I[b]	II	I	III

[a] Significantly lower yield than from superphosphate.
[b] Significantly greater yield than from superphosphate.

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