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End of Symposium

FERTILIZER PARTICLE SIZE

Crop Response to Phosphorus and Potassium in Potassium Phosphates Varying Widely in Particle Size

J. D. DeMENT[1], G. L. TERMAN, and B. N. BRADFORD

Tennessee Valley Authority, Wilson Dam, Ala.

Fusion products approximating the analyses of potassium metaphosphate (KMP) and potassium calcium pyrophosphate (KCP) were produced in pilot plants. KMP was also produced at below-fusion temperatures. Particles of these fertilizers ground rather finely were equal to potassium chloride and concentrated superphosphate as sources of potassium and phosphorus for corn grown in greenhouse cultures. Effectiveness of KMP particles coarser than −6+9 mesh and of KCP coarser than −14+20 mesh decreased markedly with further increase in size. Effectiveness of large particles was greater with surface placement than for mixing with the soil. Solubility in water was a poor index of effectiveness of KMP and KCP for plant growth.

Two types of fused potassium phosphates have been produced experimentally by the Tennessee Valley Authority: potassium metaphosphate, consisting largely of KPO_3, and potassium calcium pyrophosphate, consisting largely of $K_2CaP_2O_7$. A previous investigation (*2*) showed that potassium in fine (−35 mesh) fused potassium phosphates was equally as available as that in KCl and K_2SO_4, despite wide differences in water solubility of the potassium. Increasing the particle size to −6+9 mesh decreased the availability of the less soluble materials.

Terman and Seatz (*4*) found potassium metaphosphate to be an excellent source of phosphorus for corn, cotton, small grain, and forage crops grown in 175 field experiments on acid to neutral soils in 12 states.

This article reports results with potassium phosphates varying widely in particle size as sources of potassium and phosphorus for crops grown in greenhouse pot tests.

[1] Present address, Esso Research and Engineering Co., Linden, N. J

Materials and Methods

Fertilizers. Chemical analyses of the potassium metaphosphate (KMP), potassium calcium pyrophosphate (KCP), and other fertilizers compared in the various tests are shown in Table I. Potassium phosphates were compared with concentrated superphosphate (CSP) as sources of phosphorus and with muriate of potash (KCl) as sources of potassium.

The fused KMP fertilizers were produced in a pilot plant by burning elemental phosphorus in the presence of KCl at a temperature of about 1800° F. KCP fertilizers were similarly produced by burning elemental phosphorus in the presence of KCl and powdered phosphate rock. The resulting glasses were cooled and crushed to the desired sizes of particles. Petrographic examination indicated small amounts of unreacted KCl in the KMP and of unreacted phosphate rock and beta-$Ca_2P_2O_7$ in the KCP.

KMP glass is largely water soluble. Water solubility (the percentage of phosphorus or potassium that dissolves in a 1-gram sample in 100 ml. of water in 1 hour) of the fused materials, especially of KMP, can be varied by varying the rate of cooling and hence the degree of crystallinity. This also affects the solubility in neutral ammonium citrate (available P_2O_5 by the official A.O.A.C. method). Other studies indicate that KPO_3 is entirely water soluble, but that rate of solution is the important factor in release of potassium and phosphorus.

Three lots of KMP were also made by reacting wet-process H_3PO_4 (67% P_2O_5) with KCl at 850° to 1000° F. This method of production is less expensive than that of burning elemental phosphorus with KCl. These experimental materials consisted largely of crystals of KPO_3 and KH_2PO_4, with minor amounts of KCl and beta-$Ca_2P_2O_7$.

General Procedure in Pot Tests. All experiments were conducted on greenhouse benches at Wilson Dam, Ala. Crops were grown in No. 10 tin food cans lined with polyethylene bags, usually containing 3 kg. of soil, or soil plus sand, per can. Supplemental uniform applications of nitrogen were added as NH_4NO_3, $(NH_4)_2SO_4$, or a mixture

Table I. Chemical Analyses of Fertilizers Compared in the Experiments

Fertilizer	Experiment in Which Compared	Total P_2O_5, %[a]	K_2O Total, %	K_2O H_2O-Sol., % of Total	CaO, %	Cl, %
Produced at fusion temperatures:						
KMP	1, 3	52.5	37.9	38	0.9	4.3
KMP (impure)	2	50.2	29.1	31	9.0	4.6
KCP (impure)	1, 3	43.9	26.5	35	17.7	5.2
	2	49.0	25.1	34	17.2	4.1
Produced at below-fusion temperatures:[b]						
KMP (17B)	4	58.9	33.0	28	...	1.8
(1P)	4	53.9	37.3	27	...	4.4
(10P)	4	57.2	34.1	16	...	2.2
Other fertilizers:						
CSP	3, 4	49.8	...	...	21.3	...
KCl	1, 2	...	63.1	100	...	47.6

[a] The A.O.A.C. method for available P_2O_5 in the potassium phosphates was found to be unsuitable, except with use of less than a 1-gram sample.
[b] KMP made by reacting wet-process H_3PO_4 (67% P_2O_5) with KCl at 850° to 1000° F.

Table II. Yield of Dry Matter and Uptake of K by Corn Forage, As Affected by K Source, Particle Size, Rate, and Placement (Experiment 1)

Source and Mesh Size	Mixed through Soil—Mg. K/Pot (None)	100	200	400	800	Surface Applied—Mg. K/Pot 100	400
			Yield of Dry Matter, Grams per Pot				
KCl, −35	16.3	32.9	37.7	40.0	39.7	32.3	39.2
KMP, −35+60	...	31.3	36.0	40.6	42.6	33.1	41.1
−14+20	...	33.3	35.9	40.3	44.4	32.2	39.4
−4+6	...	31.2	36.7	38.7	42.6	32.8	39.8
1/4 inch	...	28.1	34.1	37.9	41.2	31.9	38.2
KCP, −35+60	...	31.7	38.2	39.9	41.8	32.0	39.7
−14+20	...	31.2	35.1	39.4	42.2	31.8	38.7
−4+6	...	29.5	35.6	38.7	42.3	33.6	37.0
1/4 inch	...	29.0	32.1	39.3	40.2	26.8	38.3
			Uptake of K, Mg. per Pot				
KCl, −35	66	157	266	425	747	120	401
KMP, −35+60	...	166	250	407	727	165	471
−14+20	...	149	245	437	764	175	432
−4+6	...	141	217	320[a]	549	160	411
1/4 inch	...	134	189	257	511	168	409
KCP, −35+60	...	148	229	419	677	145	378
−14+20	...	166	214	367	582	157	358
−4+6	...	131	197	279	510	135	262
1/4 inch	...	140	193	280	442	113	249

[a] Estimated value based on yields with other rates of applied K.

Table III. Average Net Uptake of K by Corn Forage (Mg. or %) per 100 Mg. of K Applied[a] (Experiment 1)

Source and Mesh Size	Mixed through the Soil	Surface-Applied
KCl, −35	91	68
KMP, −35+60	93	100
−14+20	88	100
−4+6	62	90
1/4 inch	47	94
KCP, −35+60	85	79
−14+20	88	82
−4+6	70	59
1/4 inch	64	47

[a] Yield of K with none applied deducted; based on 100- and 400-mg. rates of applied K.

Table IV. Relative Effectiveness for the First Corn Crop of K Sources Varying in Particle Size (Experiment 2)

Particle Size	Relative Effectiveness KCl	KMP	KCP
−35 mesh	100	80	98
−14+20 mesh	...	105	66
−4+6 mesh	...	71	65
1/4 inch	...	51	48
3/8 inch	...	47	42

of $Ca(NO_3)_2$ and $Mg(NO_3)_2$, phosphorus as monocalcium or diammonium phosphate, and potassium as KCl, KNO_3, or K_2SO_4. Details of each of the four experiments conducted are described in the following section.

Yields of dry matter and percentage of phosphorus or potassium in the aboveground portions of the plants were determined for all crops.

Results and Discussion

Potassium Source, Particle Size, and Placement (Experiment 1). Four sizes of particles of both KMP and KCP, and −35 mesh KCl were mixed with 1.5 kg. of Ruston sandy loam (pH 5.6), underlaid with 2.4 kg. of white builders' sand per pot. The particle sizes were −35+60, −14+20, and −4+6 mesh and approximately 1/4 inch. Particles of the last size were selected to contain 100 mg. of potassium (K) per particle. All sizes were mixed with the soil in amounts to supply 100, 200, 400, and 800 mg. of potassium per pot. In addition, 100- and 400-mg. amounts of potassium from the various sources were placed on the surface of the soil just following planting of corn on December 27, 1958. Supplemental fertilization per pot totaled 360 mg. of phosphorus and 530 mg. of nitrogen over the growth period. No consideration was given to the phosphorus content of the potassium phosphates, since previous results indicated that 360 mg. of phosphorus was adequate for good crop growth. Five single-cross hybrid corn plants were grown until February 25, 1959, at which time the plants were harvested, dried, weighed, and analyzed for total potassium.

As shown in Table II, yields of dry matter by corn with −35 mesh KCl mixed through the soil increased up to the 400-mg. application, then decreased slightly with the 800-mg. rate. Yields with all sizes of KMP and KCP increased with all rates, indicating perhaps less seedling toxicity at high rates, together with a possible effect of the larger amounts of phosphorus added with KMP and KCP than with KCl. The 1/4-inch particles of KMP and KCP produced less dry matter than the smaller sizes of all sources at the lower, but not at the higher rates of application.

Differences among particle sizes in uptake of potassium by corn were much greater than was true for dry matter. Since uptakes were linear with the applications of 0, 100, 200, and 400 mg., average net uptakes of potassium based on the 100- and 400-mg. rates were determined (Table III). With the potassium phosphates mixed with the soil, uptake from KMP decreased considerably more with increase in particle size than was true for KCP. However, with surface application, the reverse was true.

At the termination of the experiment, all particles of surface-applied KMP had been completely dissolved by the frequent additions of water to the soil surface, while residues were still evident in the soil with mixed placement. There is insufficient information on the hydrolysis and dissolution of these fertilizers to explain the observed differences in uptake of K by the corn crop. Complete dissolution of the large particles of KMP applied on the surface, however, indicates that rate of solution of this fertilizer, rather than immediate solubility in water, is important in determining availability to plants.

Potassium Sources with a Wide Range of Particle Size (Experiment 2). Impure KMP (containing some KCP) particles larger than 4-mesh were selected to contain 75 and 150 mg. of potassium (K) per particle. KCP particles were selected to contain 75, 150, 450, 3,000, and 10,000 mg. of potassium per particle. The correct amount of −35, −14 + 20, and −4 + 6 mesh fertilizers were weighed directly from the screened material. The desired application rates of 300, 450, 750, 1,500, 3,000, and 10,000 mg. of potassium per pot were obtained by supplying one or more particles per pot. All of the various combinations of rates and sources were mixed with 2 kg. of Ruston sandy loam underlaid by 1.5 kg. of white builders' sand per pot. In addition, 3/8-inch and −35 mesh particles to supply 450 and 3000 mg. of potassium per pot were placed on the surface of the soil just after planting the first crop.

Single-cross hybrid corn (five plants per pot) was grown during the following periods: first crop, July 21 to September 10, 1959; second crop, September 23 to November 18; third crop, March 14 to April 26, 1960; fourth crop, June 20 to August 3.

Supplemental fertilization was as follows for the four crops: first, 500 mg. of phosphorus as MCP and 1000 mg. of nitrogen; second, 200 mg. of phosphorus and 500 mg. of nitrogen; third, 360 mg. of phosphorus and 200 mg. of nitrogen. No corrections were made for the phosphorus added as KMP and KCP.

As shown in Figure 1, yields of the first crop of corn increased markedly with the first 300-mg. increment of potassium applied as −35 mesh KCl, KMP, and KCP. There were further small increases up to 1500 mg. of potassium applied as KMP and KCP, which may have been influenced by the increasing amounts of phosphorus added with the potassium. The 10,000-mg. applications of potassium from all three sources were toxic, as was the 3000-mg. rate of KCl. Uptake of potassium increased up to the 1500-mg. rate for KCl and the 3000-mg. rate for KMP and KCP. Toxicity at the high rates was probably due to high salt concentration, although conductivity of 1 to 1 soil-water extracts was not related to the amount of KCl applied.

Relative effectiveness values based on availability coefficient indexes calculated from Mitscherlich functions

Table V. Yields of Corn Forage with Large Particles of KMP and KCP, As Affected by Placement and Amount of Applied K (Experiment 2)

Source and Particle Size	No Applied K	Yield of Dry Matter, Grams per Pot: Mixed through soil, 450 Mg.	3000 Mg.	10,000 Mg.	Surface-applied, 450 Mg.	3000 Mg.
KMP, −35 mesh	3	38	39	...	37	40
3/8 inch	...	28	39	...	36	44
KCP, −35 mesh	...	39	42	10	38	41
3/8 inch	...	28	36	...	31	38
5/8 inch	...	26	...	...	31	...
1 inch	...	...	35	...	...	40
1 1/2 inch	...	...	...	24	...	...

Table VI. Dry Matter Yields (Grams per Pot) of Four Successive Crops of Corn Forage, As Affected by Particle Size, Source, and Rate of Applied K (Experiment 2)

Source and Particle Size	450 Mg. of K Applied: Crop 1	Crop 2	Crop 3	Crop 4	Total	3000 Mg. of K Applied: Crop 1	Crop 2	Crop 3	Crop 4	Total
KMP, −35 mesh	38	12	3	8	56	39	29	17	10	95
−14+20 mesh	39	14	3	4	59	35	26	23	14	98
−4+6 mesh	36	21	12	6	76	42	30	21	16	109
1/4 inch	33	16	12	9	71	43	28	23	17	111
3/8 inch	28	14	11	11	63	39	31	22	17	109
KCP, −35 mesh	38	14	5	4	61	42	26	18	13	99
−14+20 mesh	36	14	8	7	65	43	24	19	14	100
−4+6 mesh	35	11	8	7	62	42	28	21	15	105
1/4 inch	33	11	7	6	58	39	28	20	13	100
3/8 inch	28	11	6	6	51	36	27	19	14	96
5/8 inch	21	13	5	7	46	...	...	...	...	...
1 inch	...	...	...	...	...	35	29	18	13	95

Table VII. Yield of Dry Matter and Uptake of P by the First Crop of Corn Forage, As Affected by P Source, Particle Size, and Placement (Experiment 3)

Source and Mesh Size	No P	Mixed through Soil, Mg. of P per Pot: 70	140	280	Surface-Applied, 280 Mg. of P per Pot	Relative Effectiveness for Mixed Placement
		YIELD OF DRY MATTER, GRAMS PER POT				
CSP, −35	4.4	15.9	26.6	35.5	39.3	100
KMP, −35	...	13.5	22.4	37.5	41.0	90
−14+20	...	28.9	36.5	43.3	...	231
−6+9	...	28.0	36.6	40.3	...	207
1/4 inch	...	17.2	29.6	36.9	33.7	115
KCP, −35	...	13.9	23.6	35.1	42.6	72
−14+20	...	13.3	20.9	31.3	...	72
−6+9	...	14.7	23.3	33.1	...	84
1/4 inch	...	14.6	26.8	36.3	34.0	98
		UPTAKE OF P, MG. PER POT				
CSP, −35	4.5	18.4	33.4	45.5	58.3	100
KMP, −35	...	15.6	30.5	48.1	57.5	95
−14+20	...	28.6	43.6	51.3	...	156
−6+9	...	28.7	40.9	50.4	...	162
1/4 inch	...	15.6	29.0	42.7	47.7	80
KCP, −35	...	16.0	35.0	44.9	63.9	78
−14+20	...	15.5	27.6	36.3	...	68
−6+9	...	14.7	23.7	34.4	...	59
1/4 inch	...	13.3	30.0	42.1	47.6	71

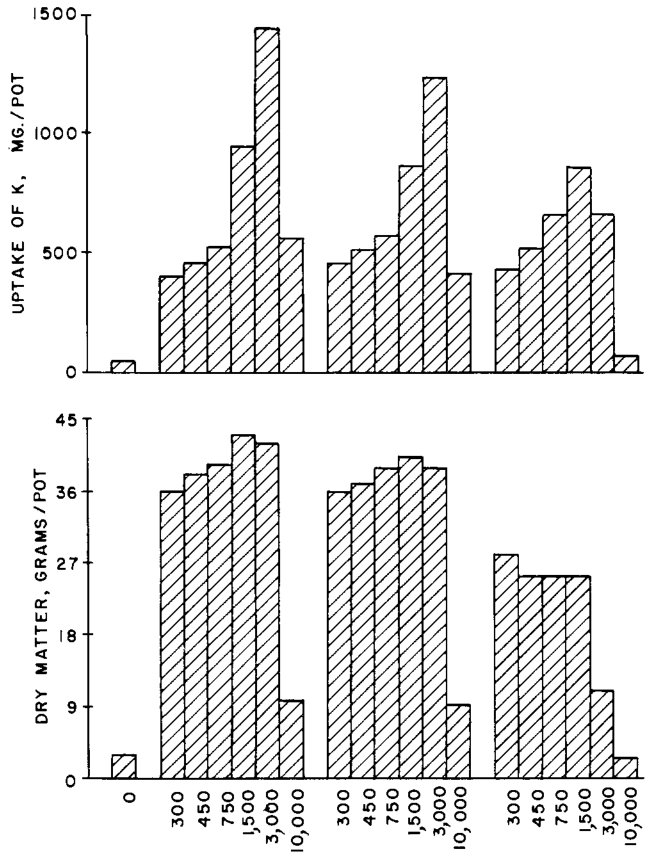

Figure 1. Yield of dry matter and K by the first crop of corn, as affected by rate (mg. of K per pot) and source of K applied as −35 mesh particles (experiment 2)

Table VIII. Yields of Dry Matter and Uptake of P by Three Successive Crops of Corn Forage, as Affected by Source and Particle Size (Experiment 3)

Source and Mesh Size	Crop 1	Crop 2	Crop 3	Total
		YIELD OF DRY MATTER, GRAMS PER POT		
CSP, −35	35.5	28.3	10.4	74.2
KMP, −35	37.5	31.1	13.7	82.3
−14+20	43.3	29.7	13.8	86.8
−6+9	40.3	24.5	14.0	78.8
1/4 inch	36.9	29.7	19.4	86.0
KCP −35	35.1	25.4	13.7	74.2
−14+20	31.3	24.8	16.0	72.1
−6+9	33.0	17.8	10.4	61.2
1/4 inch	36.3	14.7	8.0	59.0
No P	4.4	2.8	1.5	8.7
L.S.D., 5% level	2.2	2.6	2.6	...
		UPTAKE OF P, MG. PER POT		
CSP, −35	45.5	23.1	20.3	88.9
KMP, −35	48.1	23.6	20.1	91.8
−14+20	51.3	20.5	23.3	95.1
−6+9	50.4	20.0	23.0	93.4
1/4 inch	42.7	20.4	23.1	86.2
KCP, −35	44.9	19.6	20.6	85.1
−14+20	36.3	15.8	21.2	73.3
−6+9	34.4	13.4	12.8	60.6
1/4 inch	42.1	9.2	8.7	60.0
No P	4.5	2.0	1.7	8.2
L.S.D., 5% level	2.4	3.7	3.1	...

fitted to the yields of dry matter by the first crop over the range of increasing yields are shown in Table IV. The −14+20 mesh KMP was more effective for increasing yield than the −35 mesh material, but effectiveness decreased with further increase in size to 3/8-inch particles. The −35 mesh KCP was about equal to KCl in availability, but this fertilizer became less available for the first crop with all increases in size.

Because of the amounts of potassium in the particles larger than 3/8 inch, it was possible to make only certain comparisons of the availability of potassium in very large, as compared to smaller, particles. These comparisons, most of which also included mixed and surface placements, are shown in Table V. Yields with the amounts of potassium added in the 5/8-inch and 1-inch particles of KCP fell on the flat portion of the response curve, so that yield comparisons with smaller sizes and between placements are not very meaningful. However, surface placement of 3/8-inch particles of KMP and KCP and 5/8-inch particles of KCP appeared to be more effective than mixing. With −35 mesh materials, similar yields were obtained with both placements. At the 10,000-mg. rate of application, the 1½-inch particles (one per pot) were less toxic than the −35 mesh material.

Yields of the four successive crops of corn grown with various sizes and amounts of KMP and KCP applied for the first crop are shown in Table VI. It was not possible to determine whether yields with the successive crops decreased entirely because of decreasing supply of available potassium or were also affected by other factors such as high content of soluble salts in the pots. However, the higher yields with 3000 than with 450 mg. of applied potassium, especially of crops 2 to 4, indicate that lack of potassium was a major factor limiting yields. At the higher application rate, differences in total yields for the four crops among sources and sizes were rather small, and 1/4-inch particles of KMP and −4+6 mesh particles of KCP produced the highest total yields. At the 450-mg. rate, total yields were highest with −4+6 KMP and −14+20 mesh KCP, with yields decreasing with both increase and decrease in size of both sources. Maximum differences among sizes were obtained with the first crop, for which the fine sizes of both sources were best.

Phosphorus Source, Particle Size, and Placement (Experiment 3). Four sizes of particles of KMP and KCP were compared with −35 mesh CSP as sources of phosphorus for three successive crops of corn grown on Hartsells fine sandy loam (pH 5.2). The sizes were −35, −14+20, and −6+9 mesh, and 1/4 inch. Particles of the

Table IX. Yields of Dry Matter (Grams per Pot) by Three Successive Crops Grown on Hartsells Fine Sandy Loam, As Affected by Granule Size, Rate of Applied P, and Liming (Experiment 4)

Mesh Size	P Applied, Mg. per Pot	Unlimed Soil—pH 5.2 Corn, crop 1	Oats, crop 2	Oats, crop 3	Total	Limed Soil—pH 7.5 Corn, crop 1	Oats, crop 2	Oats, crop 3	Total
No P	0	4.3	3.6	4.1	12.0	4.1	4.8	4.4	13.3
CSP, −28+35	60	18.4	10.5	7.0	35.9	10.5	12.9	6.4	29.8
	120	29.6	15.1	9.5	54.2	16.0	18.0	8.6	42.6
CSP, −6+14	60	17.7	10.6	6.6	34.9	10.0	12.5	6.4	28.9
	120	28.4	14.5	8.9	51.8	15.4	16.9	7.6	39.9

Table X. Relative Effectiveness of CSP and KMP Based on Concurrent Linear Slopes of Yields of Dry Matter on the 60- and 120-Mg. Rates of Applied P (Experiment 4)

P Source	Water-Soluble P, % of Total	−28+35 Mesh Granules				−6+14 Mesh Granules			
		pH 5.2		pH 7.5		pH 5.2		pH 7.5	
		Crop 1	Crops 1–3	Crop 1	Crops 1–3	Crop 1	Crops 1–3	Crop 1	Crops 1–3
CSP	91	100	100	100	100	100	100	100	100
KMP (17B)[a]	25	81	84	93	99	79	86	111	99
KMP (1P)[a]	16	79	80	103	102	75	86	67	81
KMP (10P)[a]	9	84	83	111	103	96	98	87	88

[a] Below-fusion temperature products made with H_3PO_4 and KCl.

largest size were selected to contain 70 mg. of phosphorus per particle. Each source was mixed with 3 kg. of soil in amounts to supply 70, 140, and 280 mg. of phosphorus per pot. In addition, the −35 mesh particles of all three sources and $^1/_4$-inch particles of KMP and KCP were applied to the surface of the soil in amounts to supply 280 mg. of phosphorus per pot. Supplemental fertilization per pot totaled: first crop, 500 mg. of potassium and 700 mg. of nitrogen; second crop, 200 mg. of potassium and 200 mg. of nitrogen; third crop, 300 mg. of nitrogen.

Five single-cross hybrid corn plants were grown for each crop as follows: August 4 to September 29, 1959; October 5 to December 7; and December 14 to February 24, 1960. Second and third crops were grown only on pots initially receiving 280 mg. of phosphorus per pot.

Yields of dry matter and uptake of phosphorus by the first crop of corn are shown in Table VII. At the 280-mg. rate of phosphorus, yields of dry matter with −35 mesh CSP, KMP, and KCP were higher when surface-applied than when mixed with the soil, but mixing resulted in higher yields with $^1/_4$-inch particles of KMP and KCP than did placement on the surface. Uptake of phosphorus by the crop was higher for all sources and sizes with surface placement. As was the case with these fertilizers as sources of potassium in experiment 1, an adequate explanation is not apparent.

Effectiveness of the experimental fertilizers relative to CSP was estimated from Mitscherlich functions fitted to yields of dry matter and uptakes of phosphorus by the method described by Bouldin and Sample (*7*). These values are also shown in Table VII. Effectiveness of the −35 mesh fertilizers in terms of both yield and uptake decreased as follows: CSP > KMP > KCP. The −14+20 and −6+9 mesh KMP was more than twice as effective and the $^1/_4$-inch particles slightly more effective than fine CSP. These differences apparently result from two factors, both of which enter into availability of the phosphorus to plants. One is greater reaction of the fine phosphates with soil; the second is the slower dissolution of the large particles.

Effectiveness of KCP as a source of phosphorus was considerably less than for the corresponding sizes of KMP.

Yields of dry matter and uptake of phosphorus by the first crop of corn fertilized with 280 mg. of phosphorus from each source and residual yields of the second and third crops are shown in Table VIII. Total yields of dry matter for the three crops fertilized with the four sizes of KMP were similar and greater than the yields with CSP and all sizes of KCP. Residual yields with coarse KMP was relatively greater than with the other fertilizers, which indicates a gradual hydrolysis of the KMP over time. However, the reverse was true for coarse KCP, with which yields of the third crop fell off markedly. This may indicate a precipitation of $Ca_2P_2O_7.4H_2O$ or other water-insoluble degradation product of KCP, resulting in lowered availability. Presumably, this might also happen with KMP in a soil high in soluble calcium, but there was no indication of this with KMP in the acid Hartsells soil used for the experiment.

KMP Produced at Below-Fusion Temperatures (Experiment 4). CSP and three lots of KMP made by reacting wet-process H_3PO_4 with KCl at temperatures below the fusion point were compared as sources of phosphorus. Two particle sizes, −28 + 35 and −6 + 14 mesh, were mixed with unlimed Hartsells fine sandy loam (pH 5.2). This was soil heavily limed to pH 7.5 in amounts to supply 60 and 120 mg. of phosphorus per pot containing 3 kg. of soil. Five plants of single-cross hybrid corn were grown from November 25, 1960, to January 30, 1961. This crop was followed, without further addition of phosphorus, by two crops of 30 Minhafer oat plants grown from February 21 to April 19, and from April 28 to June 15. Supplemental fertilization totaled as follows, per pot: first crop, 500 mg. of nitrogen and 300 mg. of potassium; second crop, 400 mg. of nitrogen and 100 mg. of potassium; third crop, 300 mg. of nitrogen and 100 mg. of potassium.

Table IX shows the yield responses of corn, followed by two crops of oats, to CSP on unlimed Hartsells fine sandy loam, and this soil limed to pH 7.5. Differences between granule sizes were minor, both with CSP and the KMP materials. Yields were lower at pH 7.5 than 5.2, apparently due to temporary reduction in nutrient availability resulting from heavy liming just prior to planting the first crop.

Since yields of corn and total yields of the three crops were essentially linear with the 60- and 120-mg. rates of applied phosphorus, concurrent linear slopes were calculated. Relative effectiveness values based on these slopes are shown in Table X. Crop response to the low-temperature KMP fertilizers ranged from 79 to 111% of that for CSP, with variability due to differences in granule size and liming of the soil.

In a previous short-term, potassium-uptake test (*3*) with oats fertilized with the same fertilizers, relative availabilities of K in $-6+9$ mesh particles made with elemental phosphorus and KCl and with H_3PO_4 and KCl were 46 and 41%, respectively, of potassium in KCl. Availability of potassium in the -35 mesh materials was equal to that in KCl.

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GRANULAR FERTILIZER

The Influence of Associated Salts on Plant Response to Dicalcium Phosphate

D. R. BOULDIN[1] and E. C. SAMPLE
Tennessee Valley Authority, Wilson Dam, Ala.

The influence of granulating nonphosphatic salts or glass beads with dicalcium phosphate on plant response to phosphorus was studied in greenhouse culture. Plant response to the several fertilizers was positively correlated with the geometric surface area of the fertilizers. The results indicate that dicalcium phosphate and nonphosphatic salts should be mixed prior to granulation so that each granule contains both components.

In previous studies (*1–3*), plant response to dicalcium phosphate and to other A.O.A.C. water-insoluble phosphates has been correlated with the estimated geometric surface area (*4*). When mixtures of monoammonium phosphate and dicalcium phosphate were studied, plant response to the dicalcium phosphate was also well correlated with the geometric surface area of granules formed from a mixture of the two phosphates (*1*). The objective of the experiment reported here was to study plant response to granular dicalcium phosphate fertilizers with geometric surface area varied by additions of several nonphosphatic salts or glass beads.

Methods and Materials

Fertilizers. A bulk sample of anhydrous dicalcium phosphate was prepared as follows: a 9% solution of H_3PO_4 was saturated with reagent-grade dicalcium phosphate at room temperature. After filtering, the solution was heated with stirring to about 90° C. The anhydrous dicalcium phosphate was filtered off and washed with dilute H_3PO_4 and acetone. The crystal size was less than 100 microns.

Dicalcium phosphate was granulated by moistening with 5% agar solution, pressing the moist mixture into pellets with a hydraulic press, and screening the crushed pellets after drying. Mixtures of 40-micron glass beads and anhydrous dicalcium phosphate were granulated by the same procedure.

Reagent-grade salts ground to pass a 35-mesh screen were mixed with dicalcium phosphate. The mixture was moistened with water and granulated as described above.

The number of granules per gram was determined by counting weighed samples. Bulk density was determined as follows. A weighed sample of the granular fertilizers was mixed with 40-micron glass beads, and the volume of the mixture was determined after careful packing in graduated cylinders. The weight of the mixture was also determined. By using the measured bulk density of the glass beads and these data, the bulk density of the fertilizers was calculated according to Equation 1

$$D = \frac{W_F D_B}{V D_B + W_F - W_T} \tag{1}$$

where

D = bulk density of fertilizer
D_B = bulk density of beads
V = volume of fertilizer and bead mixture
W_F = weight of fertilizer
W_T = weight of fertilizer and bead mixture

The geometric surface area was calculated from bulk density and number of granules as follows. Granules were assumed to be spherical in shape. Using this assumption, mean radius is given by Equation 2

$$R = \left(\frac{3}{4\pi N D}\right)^{1/3} \tag{2}$$

where
R = mean radius in cm.
N = number of granules per gram of fertilizer
D = bulk density in grams per cm.^{3}

By using the value of R given by Equation 2, the geometric surface area per gram of fertilizer is given by Equation 3

$$GSA = (4\pi N)^{1/3} \left(\frac{3}{D}\right)^{2/3} \tag{3}$$

where

GSA = geometric surface area, cm.^{2} per gram

Characteristics of the fertilizers are listed in Table I.

Experimental Procedure. Samples of the fertilizers to supply 30 and 60 mg. of P were mixed with 3 kg. of Hartsells fine sandy loam (pH 5.2), and the mixture was placed in No. 10 tin cans lined with plastic bags. In addition, treatments containing 90 and 120 mg. of P as $-28+35$ mesh anhydrous dicalcium phosphate, and a no-phosphorus check were included to establish a response curve. Three replications of each treatment were prepared. Nitrogen and potassium levels were equalized at 200 mg. per culture using solutions of $Ca(NO_3)_2$ and $Mg(NO_3)_2$ and K_2SO_4. Oats were seeded and the cultures grown for 8 weeks in the greenhouse. One hundred milligrams of nitrogen as a

[1] Present address: Department of Agronomy, Cornell University, Ithaca, N. Y.