International
Fertilizer Industry
Association

ISMA* Technical Conference

The Hague, The Netherlands
13-16 September 1976

*In 1982, the name of the International Superphosphate Manufacturers' Associations (ISMA)
was changed to International Fertilizer Industry Association (IFA).

UTILIZATION OF DIFFICULT PHOSPHATE ORES

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INTRODUCTION

There has always been an interest in using phosphate ores which are
awkward to process because of difficult impurities. This is because they
are indigenous and therefore usually relatively inexpensive. But studies
were only spasmodic until 1973 when substantial price rises for the rocks
sold internationally occurred. This triggered development programs in
many countries to use the difficult indigenous ores.

The utilization of difficult phosphate ores for fertilizer manufacture
is a major topic of the R & D program of the Technology Division of the
International Fertilizer Development Center (IFDC). We think it will be
worthwhile to explain a little about the work of our organization, which
was set up in October 1974.

IFDC is a private, nonprofit organization located at Muscle Shoals,
Alabama, adjacent to the Tennessee Valley Authority's National Fertilizer
Development Center (NFDC). IFDC's goal is to improve fertilizers and
fertilizer know-how in developing countries through development, collection,
adaptation, and dissemination of fertilizer technology. Emphasis will be
placed on finding more efficient fertilizers for tropical agriculture,
improving utilization of indigenous raw materials, and lowering processing
and distribution costs.

IFDC has three divisions: Agro-Economic, Outreach, and Technology,
and their work will be closely related. The Technology Division will
participate heavily with the Outreach Division in technical assistance
programs which will apply present and future technology to the problems
of countries and organizations in need of help.

In formulating a program we recognize that the field is a large one,
and that a single organization cannot conduct effective research and
development on a wide range of problems. It should be understood that the
tentative program is likely to involve cooperation with many organizations,
and that to a large extent IFDC expects to concentrate its own experimental

work on projects which will complement the work of others. This will require that we keep in close touch with technical developments throughout the world.

THE IFDC PHOSPHATE ROCK PROGRAM

The 1973-74 shortage of phosphate rock and the simultaneous spectacular rise in prices have caused many developing countries to seek indigenous sources. Many new deposits have been found and previously known deposits are being reconsidered. At the present time, the shortage is past and has been replaced by a surplus. World market prices have declined substantially. Planned phosphate rock mining capacity seems more than adequate to supply forecast demand at least through 1980. Nevertheless, many developing countries are placing a high priority on developing their indigenous deposits, particularly those countries which have a substantial domestic demand or regional market potential.

There are several reasons for this renewed interest in opening new phosphate deposits even when there is a surplus supply. First, there is the natural desire to be independent of foreign sources; the developing countries will not soon forget the lessons learned during the shortage when they were at the mercy of foreign suppliers. Second is prospective savings in foreign exchange and increased domestic employment. Third, although world market prices have declined, it is likely they will remain substantially higher than the pre-1973 level; and freight costs on indigenous supplies will be lower than for imported rock and not subject to international freight rates. These factors combine to improve the economics and desirability of utilizing indigenous deposits. Many of these considerations also apply to developed countries, but IFDC's main concern is with those countries which need technical assistance.

Most of the new deposits present some problems in mining, beneficiation, and use in conventional processes. Therefore, we expect that a large part of IFDC's program will consist of finding good uses for indigenous phosphates and dealing with associated technical problems.

The principal phosphate fertilizer products in commercial use in the world today, in the approximate order of their P_2O_5 volume, are:

    1.   Phosphoric acid and its derivatives:

        a.   ammonium phosphates

        b.   triple superphosphates

    2.   Single superphosphates.

3. Nitrophosphates.

4. Basic slag.

5. Ground phosphate rock for direct application.

    a. raw apatitic rock

    b. calcined aluminum phosphate ore

6. Sintered alkali-rock phosphate materials (mainly Rhenania phosphate).

7. Fused calcium magnesium phosphate.

8. Defluorinated phosphate rock.

9. Dicalcium phosphate.

World popularity for a given process or product cannot necessarily be equated to usefulness in developing countries or in a particular country. There may be special combinations of raw materials and energy or special agronomic advantages that would favor less common processes or even processes that so far have not progressed beyond experimental stages.

Nevertheless, the preeminent place of phosphoric acid and its derivatives has led us to devote a substantial portion of our program to means for utilizing phosphate rock for production of wet-process phosphoric acid, without neglecting other processes.

Several types of phosphate ores have been identified that are difficult to use for wet-process acid production. Such ores are sometimes lumped together under the classification of "low-grade" phosphate ores, although the difficulty is not usually directly connected with the grade itself.

COMMON TYPES OF DIFFICULT ORES

Now we will describe the most common types of difficult ores and briefly discuss problems of using them. We wish to emphasize that this classification does not purport to be a complete listing of all ores that may cause some difficulty in beneficiation or use. Also, we recognize that many ores may present a combination of difficulties and thus fall within two or more of the categories.

High-silica ores

Ores high in silica which are difficult or expensive to beneficiate may pose a problem. However, if the silica is present in an unreactive form, it will not normally cause any special problem in the phosphoric acid production process if the plant is designed with sufficient filtration and washing

capacity to remove the silica with the calcium sulfate filter cake. In such cases the problem becomes one of economics; whether the additional cost of using the ore without beneficiation (or with minimum beneficiation) is less than the cost of removing the silica by beneficiation. Naturally the loss of phosphate values incurred in beneficiation must also be taken into account. So also must any costs and environmental problems associated with the disposal of the silica- and phosphate-containing waste. The answer to this problem is likely to depend on several factors; but we suspect it will often be preferable to use the high silica ore without extensive beneficiation, particularly when the fertilizer manufacturing plant can be located at or near the mine and the effect on transport costs of lowering of grade due to silica is small. IFDC hopes to have an answer to this question in one specific case soon.

Nitrophosphate processes can accept high-silica ores by providing a simple silica removal step following the nitric acid digestion step. The cost of this additional equipment is usually a small percentage of the total plant cost.

When the silica is present as silicates of acid-soluble cations, the problem is different; for instance, ores with high clay content may fall into the "high R_2O_3" category. We shall consider them under that heading.

Organic matter

Organic matter in phosphate rock can cause difficulty in wet-process acid production by giving rise to foaming and by forming a sludge which interferes with filtration. It may also cause further difficulties in downstream storage and processing. The extent of the difficultuies depends on the quantity and character of the organic matter. Examples of such ores are found in some north African deposits, in Colombia, and in North Carolina and western states of the United States.

Organic matter can be removed by calcining at a moderate temperature [1]. The organic matter supplies part of the fuel required for calcining. For example, in some U.S. Western rocks there is sufficient organic matter to supply all or nearly all of the fuel needed for calcining by the fluidized bed technique.

Another method for removal of organic matter is flocculation or polymerization during digestion which permits removal of organic matter during gypsum filtration without interfering with rapid removal and washing of the latter [2].

Ores of high iron/aluminum content

Ores high in iron and aluminum are normally regarded as unusable in wet-process phosphoric acid manufacture when the R_2O_3 ($Fe_2O_3 + Al_2O_3$) exceeds a certain proportion, which is usually placed at 3-5%. It is interesting that in the 1850's rocks from Redonda and Sombrero containing high R_2O_3 were preferred for making wet acid in England because of their softness and hence ease of grinding. However, the main use of the acid was to produce elemental phosphorus by heating the concentrated acid with charcoal. For this purpose the iron and aluminum content of the acid was not critical.

The first known commercial use of wet-process phosphoric acid for fertilizer production was in Germany in the 1870's to utilize the native Lahn deposits which were too low grade and high in R_2O_3 to make satisfactory superphosphate. A weak sulfuric acid was used to extract the phosphate without undue amounts of iron and aluminum passing into solution. The phosphoric acid separated needed considerable evaporation and was then used to make triple superphosphate.

Many ore deposits in this classification cannot be beneficiated satisfactorily. The problem also results from the mineralogical forms in which the iron and aluminum are present, for example, as phosphates, silicates, oxides or other minerals. Beneficiation methods, if they can be used at all, include magnetic separation (e.g., to reduce magnetite content) and de-sliming (to reduce iron and aluminum present as silicates, i.e., clays). These two beneficiation methods are well known and will not be discussed here. But two other promising methods for using phosphate ores high in R_2O_3, without a beneficiation step at all, are under development today and illustrate some of the opportunities for using two important categories of difficult ores.

Ores high in aluminum/iron phosphates

Deposits of this kind occur on Christmas Island (about 50 metric tons [mt]), in Senegal and other west African countries (several 100 mt), in Brazil and elsewhere. The phosphate minerals in these deposits vary from one deposit to another; in general they are complex, hydrous phosphates of aluminum and/or iron, often containing other elements such as calcium and sodium. The more common minerals are crandallite, millisite, wavellite, pallite, and cocoxenite. The compositions of two typical ores are:

Christmas Island C grade, P_2O_5 26-28%, CaO 12-24%, R_2O_3 33-43%

Senegalese Thies rock, P_2O_5 26-30%, CaO 8-9%, R_2O_3 37-40%.

Both have combined moisture content of about 15%. It will be noted that the R_2O_3 and P_2O_5 are present in chemical combination, and therefore it is impossible to dissolve the phosphate without the iron/aluminum also passing into solution.

Ion exchange is a promising technique for dealing with iron and aluminum in solution when phosphate rock high in R_2O_3 has been dissolved in acid. The Danish company, Superfos, has applied the method on a full plant scale for more than 4 years; a potassium-loaded exchanger is used to remove calcium from the solution obtained by dissolving conventional phosphate rock in nitric acid. In this case the proportion of Fe/Al to Ca is relatively low and the cation exchanger has to deal mainly with calcium. But when rocks containing crandallite and millisite are dissolved to give a nitrophosphate solution, the iron and aluminum are often present in far higher proportion than the calcium.

Furthermore, the total amount of the three cations per unit of P_2O_5 is considerably higher in crandallite and millisite than in ordinary phosphate rock. This means that a correspondingly higher $K_2O:P_2O_5$ ratio will result if all the cations are replaced by potassium. Superfos is working on modifications to its ion exchange process which, if successful, will permit the exploitation of high Fe/Al phosphates. This will be especially attractive if a valuable Al-containing coproduct can be obtained.

It will be appreciated that the ion exchange process can be applied to acid solutions containing iron and aluminum no matter what the original chemical forms of the two cations. Indeed, in the short run the ion exchange process may find its next application to ores in which the R_2O_3 is marginally high at 5-10% rather than to those in which it is in the 30-40% range. There are many ores in which the main phosphate constituent is fluorapatite and the R_2O_3 occurs as relatively minor contents of phosphates, oxides or silicates.

A well-known and established method of converting high aluminous ores to a more effective source of fertilizer phosphate is by calcination and grinding. Senegalese Thies ore is treated in this way and the product is finding increasing application as an alternative to basic slag. None of the phosphate in the calcined rock is water soluble but roughly three-quarters of it is soluble in alkaline ammonium citrate.

Ores high in nonphosphatic iron/aluminum minerals

Deposits of high R_2O_3 content in which the iron and alumina are present in nonphosphatic minerals occur in many countries including Iran, India,

United States, Canada, Brazil, and USSR. The deposits include ores of
igneous origin (some of which are weathered), as well as sedimentary and
metamorphic ores. The iron may be present as hematite, magnetite, limonite,
goethite, ilmenite, or pyrite. Both iron and aluminum may be present as
complex silicates, such as micas, feldspars, pyroxenes, and various clay-
type minerals. While some of these ores can be beneficiated by conventional
means, many cannot.

An interesting process for using ores of this kind directly in fertil-
izer manufacture has been developed by National Process Industries (Pty.)
Ltd. [3]. In the basic process the ore, with or without a pretreatment, is
attacked with nitric acid under controlled conditions of concentration,
temperature and time, and according to a treatment regime, which results in
a nitrophosphate liquor containing no more than 10 parts by weight of R_2O_3
in solution per 100 parts P_2O_5 by weight, even from rocks of 20% R_2O_3
content. The ratio of $R_2O_3:P_2O_5$ which can be obtained is usually under
5:100. The pretreatment includes calcination and is designed to convert
contaminating minerals such as hydrated oxides or carbonates to relatively
insoluble oxides. The nitrophosphate solution, after separation of the
insoluble oxides, can be worked up by known methods to give NP or NPK
fertilizers; or for example, solvent extraction can lead to phosphate
chemicals and a byproduct nitrate solution suitable for conversion to a
nitrogen-containing fertilizer.

The process has particular merit when applied to ores which for one
reason or another cannot be beneficiated by magnetic separation or other
conventional methods. It has been applied successfully to an ore of the
following composition: P_2O_5 30%, Fe_2O_3 18%, SiO_2 4%, CaO 43%, Al_2O_3 2%.

Some of the silicate minerals are relatively insoluble in mineral acids.
In recent laboratory tests, promising results were obtained in preferential
extraction of P_2O_5 with sulfuric acid when the aluminum was present mainly
as muscovite.

When the iron and aluminum are present mainly as clay-type minerals,
calcination is likely to be necessary to render these elements relatively
insoluble and also to ensure good filtration rates after acid digestion.
Tennessee ore is an example. In bench-scale studies, TVA has extracted
calcined Tennessee ore containing 18% P_2O_5, 8% Al_2O_3 and 5% Fe_2O_3 by mixed
nitric-sulfuric acids. All the P_2O_5, 28% of the Al_2O_3 and 15% of the
Fe_2O_3 were dissolved.

High-carbonate ores

Ores containing a high percentage of carbonates, particularly calcite and/or dolomite, may be uneconomical to process because of the high consumption of sulfuric acid. In the case of dolomite, the presence of high percentages of magnesium in the phosphoric acid may sometimes lead to difficulties in downstream processing. By some estimates, 75% of all sedimentary ores are in this high-carbonate category. In many cases the choice may lie between accepting the high acid consumption and beneficiation. Beneficiation may be accomplished by calcining to decompose the carbonates followed by removal of the oxides (or hydroxides) by washing or air separation. Calcining requires a substantial amount of fuel, especially for ores of very high carbonate content. This is a serious drawback in most countries.

Recently a process for removal of calcite by flotation was developed in Brazil [4] and is successfully used in a commercial plant at Jacupiranga where the ore contains only about 12% apatite (5% P_2O_5), 71% calcite, and 7% dolomite [5]. A high-grade apatite concentrate (about 36% P_2O_5) is produced and used for wet-process phosphoric acid production, and the calcite is used for cement production. The P_2O_5 recovery in the concentrate is about 76%. Experiments are in progress in Brazil to determine whether the flotation process can be adapted successfully to other high-carbonate ores. Good results have been achieved with several other ores by some modification of the flotation process [6]. The process seems to work best on ores containing well-crystallized carbonates. When the ore contains soft or chalky carbonates, the results are less satisfactory.

High-chloride ores

Many phosphate ores are high in chloride, and this can contribute to severe corrosion in wet-process phosphoric acid plants. Examples are found in Peru, Syria, Jordan, Israel, and Sri Lanka, all of which are currently being exploited or have good potential for exploitation. The chloride is usually present as water-soluble salts, such as NaCl, although some ores contain chloride substituted for part of the fluoride in the apatite structure, in which case the chloride is water insoluble. The amount of chloride that can be tolerated without excessive corrosion naturally depends on the materials of construction in the phosphoric acid plant. The tolerable limit

also depends on the character of the rock which may augment chloride corrosion by release of free hydrofluoric or fluosilicic acid or sulfides. In most of the rocks used today, the limit is in the range of 0.02-0.10% Cl when conventional stainless steels are used for plant construction. By using special materials of construction, higher chlorine percentages can be tolerated.

Soluble chlorides in phosphate ores can be removed by washing with water, although complete removal is sometimes difficult. However, some of the world's deposits of high-chloride ores occur where fresh water is very scarce or entirely lacking. Some of these ores do not require washing for beneficiation, and washing to remove chloride may result in high P_2O_5 losses. In some cases washing with sea water is done to remove clays and similar impurities and then a final wash with fresh water removes most of the chloride introduced by the sea water.

When high-chloride ores are to be converted to phosphoric acid at or near the mine, it could be more economical to build the plant of corrosion-resisting materials than to remove chlorides. Various alloys and plastic materials have been used to improve on the corrosion performance of the 316 and 317 type stainless steels. The latter are the standard alloys used in di-hydrate phosphoric acid plants when chloride in rock is satisfactorily low. Two more resistant types of alloys are exemplified by Uranus B6 and Ferralium with the following compositions:

	UB6	Ferralium
	%	%
Cr	20	25
Ni	25	5
Mo	4-5	2
Cu	1.5	3
C max	0.02	0.06

In tests on a series of rocks of different chloride contents, UB6 gave good results (corrosion less than 0.2 mm/yr) with chloride content in rock under 0.1%, fairly good results (corrosion up to 3 mm/yr) when chloride contents were in the range 0.1-0.2%, and poor results (corrosion up to 10 mm/yr) when chloride exceeded 0.3%. It will be appreciated that while chloride is a major contributor to increased corrosion other factors including hydrofluoric acid are important. Moreover, simulated corrosion

tests can be no more than a rough guide to actual plant performance with its own special features associated with rock composition, erosion conditions, process control, etc.

We have had many favorable comments on the good performance of Ferralium, which many fertilizer manufacturers point out has a good combination of corrosion resistance, hardness, erosion resistance, and price. It, therefore, offers distinct advantages over both the conventional austenitic stainless steels and the more specialized high-nickel alloys. It is widely used in the fertilizer industry and others for pumps and agitators and is used to some extent for other applications.

IFDC is making a survey of the effects of chloride on alloy corrosion in phosphoric acid manufacture and the added effects attributable to free sulfuric acid, hydrofluoric acid, and fluosilicic acid. A survey of the use of inhibitors such as cupric ion will be included. Experimental work will include studies of those factors using the best of the alloys in use today along with other promising materials of construction.

When phosphate ores high in chloride are to be exported, it may be useful to induce the buyer to wash the ore. Naturally, he must be offered some financial incentive to offset the cost of washing. It will be a sensible course to take, for example, if clean water is expensive near the mine or if the buyer intends to practice wet grinding and can therefore wash out the chloride at the same time. Another alternative would be to ship the ore to a well-located distribution point where there is an ample supply of fresh water for washing. The ore could be stockpiled, washed, dried, and distributed to users.

Some of the well-established gypsum filters have been tried for chloride removal and the continuous rotary table types are reported to give good results. Recently a new design specifically for chloride removal has come forward. The process involves stirring the rock with water prior to pumping it to the filter which is equipped with water-washing arrangements. The wash waters all go to a settling unit from which the overflow is discarded and the underflow is returned to the washing tank. The damp rock is removed from the filter for use or for drying prior to shipment. The filter itself uses a microperforated metal table for the filtration surface and operates under vacuum with a hydraulic seal; there is no filter cloth. The filter is therefore of relatively simple construction and produces a dewatered ore at about 15% moisture content. It is claimed that ore of chloride content 0.6% can be reduced to 0.06% with a utilization of 350

liters wash water per ton of dry rock. There is therefore relatively low consumption of process water and phosphate losses are also very small.

ASSESSMENT OF THE RELATIVE VALUES OF PHOSPHATE ORES

Sometimes a phosphoric acid plant is being designed for a geographic location where a number of phosphate ores, some upgraded and some not, are available as feedstock. In such a case a good choice has to be made which takes into account not only the extra costs of using the lower-grade ores in the plant as compared with the costs of beneficiating to produce a higher-grade product. These latter costs include not only the capital charges and operating costs of the beneficiation plant but also the phosphate losses and the environmental problems associated with the rejected matter.

To enable the relative merits of the various possible courses of action to be compared, Messrs. Cremer and Warner [7] have for some years used a procedure for assessing the relative values of a group of phosphate ores for phosphoric acid manufacture. In this procedure a standard 75 BPL rock, with a known market value per ton, is taken as the basis; but any other standard can be adopted for a particular study. Very briefly, the procedure involves making deductions from the 75 BPL standard value for the following shortcomings of a lower-grade rock (the examples given may not cover the whole range in any particular case):

1. Lower P_2O_5 content, meaning that more tonnage has to be bought and handled.
2. Lower P_2O_5:CaO ratio (with adjustment for sulfate content), leading to higher sulfuric acid usage.
3. Higher chloride content, leading to higher capital charges and maintenance.
4. Higher clay content, leading to lower plant capacity and often to lower raw materials efficiency.
5. Greater hardness or particle size or lower grade, leading to higher grinding cost.

Using this kind of approach, the best-value ores can be identified and the costs of improving ores compared with the benefits of using them in the unbeneficiated condition.

MORE EFFECTIVE PRODUCTS FOR TROPICAL AGRICULTURE

The fertilizers used in the world today are mainly those which have
been developed for agriculture in temperate zones. One of the major
concerns of IFDC will be to identify or develop fertilizer products which
are more effective for tropical agriculture than those commonly used in
temperate climates.

Tropical soils vary widely, but a large percentage of them are strongly
acid. Probably more than half of potentially productive tropical soils are
acidic, some of them with pH in the range of 3.5-4.5. There is some reason
to believe that conventional soluble phosphate fertilizers are not always
the most effective on such soils. For instance, Rhenania phosphate has been
reported to be substantially more effective than superphosphate on several
tropical soils in Costa Rica, Liberia, Congo, Zaire, Ghana, and Malawi [8].
The superiority of Rhenania phosphate on these strongly acid soils was
attributed to resistance to fixation by the soil, owing to the complex
binding of the phosphate to lime and silicate.

Sulfur is often deficient in tropical soils, and in such cases single
superphosphate may be a good choice.

Fused calcium magnesium phosphate may give superior results on some
soils, possibly due to the magnesium content or its soluble silicate content.

Direct application of phosphate rock may often be the most economical
means of phosphorus fertilization on acidic tropical soils if the reactivity
of the rock is adequate.

In addition to the above illustrations, there are numerous other
possibilities which should be considered in arriving at the best means
for meeting the fertilizer needs for any specific developing country or
region. Naturally, the problems connected with utilizing indigenous ores
depend on the process selected. Conversely, selection of a process may
depend on suitability of the indigenous ore, among other factors.

Ores that are difficult to use for phosphoric acid production may
present little difficulty in other processes. For instance, it is claimed
that the Rhenania process can be adapted to phosphate rock of any
composition, although the grade of the product naturally depends on the
grade of the ore.

For single superphosphate production, the chloride content is
relatively unimportant but the grade and reactivity become more important.

DIRECT APPLICATION OF PHOSPHATE ROCK

In view of accumulating evidence that highly reactive ground rock may
be as effective as the more expensive soluble phosphate fertilizers in many
developing countries, a substantial portion of IFDC's program will be
directed toward evaluation of various phosphate rocks for this purpose in a
variety of tropical soils.

The principal advantage of ground rock is its low cost. Phosphate
rock may cost only about half as much per unit of P_2O_5 as does triple
superphosphate when both must be imported; when indigenous rock is available,
the cost may be even lower.

Other advantages are:
1.   Very low capital investment for processing.
2.   No particular technical skills are required.
3.   Small energy requirement.
4.   Little or no loss in processing.
5.   Rocks unsuitable for chemical processing are in some cases
      suitable for direct application.
6.   The long delay involved in constructing chemical processing
      plants can be avoided.
7.   Economy of scale is relatively unimportant.

In the fertilizer year of 1971-72, phosphate rock used for direct
application accounted for about 1.7 million tons of P_2O_5, about 7.6% of
the total P_2O_5 fertilizer used [9]. Despite this relatively small
percentage, phosphate rock is an important fertilizer material in many
developing countries and may become more so with proper guidance.

Use of phosphate rock has been rather thoroughly investigated in the
United States with generally indifferent results. However, three factors
should be taken into account:
1.   The majority of the tests were made with Tennessee or
      Florida rock, which are not very reactive. In recent field
      tests, North Carolina rock was reported to be 73-100% as
      effective as superphosphate on acid soils, while Florida
      rock was much less effective [10].
2.   Most of the tests were made on neutral or moderately acid
      soils, or in combination with limestone application; in many
      tropical countries soils are strongly acid and limestone
      application is not economically feasible.

3. The U.S. conditions are unusually favorable for the use of chemically processed fertilizers due to ample supply and relatively low cost.

One of the more important developments is a more accurate method for evaluation of the reactivity of phosphate rocks that has been developed by TVA [11]. Some refinements are needed, particularly in the area of finding simpler methods.

The agronomic effectiveness of an apatitic rock depends strongly on its reactivity and on the acidity of the soil. Even rocks of medium to lower reactivity may be economically useful if they are available at low cost and the soils are strongly acid.

IFDC is continuing its efforts to develop methods for rapid and accurate evaluation of reactivity of rocks for the guidance of developing countries. These methods will be correlated with the results of agronomic tests which are in progress in tropical areas by several international and national agricultural research organizations. Also, basic studies of chemical reaction of phosphate rocks in various soils and their effect on the phosphorus level in soil solutions are being undertaken in IFDC laboratories.

Another problem requiring attention is the relationship of fineness of grinding to agronomic effectiveness. It is known that there is some relation between particle size and agronomic response, but the need for extremely fine grinding requires further study, especially for tropical soils.

One of the drawbacks of phosphate rock for direct application is that it must be more or less finely ground to be effective. Finely ground rock is dusty and ill-suited to use in mechanical spreaders. This disadvantage may be of minor importance in countries where manual spreading is common. However, some countries prefer granular materials and methods of granulating finely ground rock have been developed. But in nearly all cases where data are available, the granular product has proven much less effective than the finely ground rock, at least during the first year after application. IFDC's program includes studies for tackling this problem by:

1. Production of granules which disintegrate rapidly in the soil.
2. Studies of relatively small granules.
3. Granulation with acid-forming materials.
4. Application of ground rock in slurry form.

PHOSPHATE ROCK AND MYCORRHIZAS

Another important area for future development is that concerned with phosphate rock and mycorrhizas used together. Research workers [12] have observed improvements in "insoluble" phosphate utilization by plants when using soils infected by certain strains of mycorrhizas. Unfortunately, almost all of the work done to date has been in the hands of men who were far more interested in mycorrhizas than in defined phosphate sources. And so the findings are often difficult to compare and to interpret insofar as rocks are concerned. But certain very tentative forecasts might be made.

1. Rocks of low reactivity will not have their value for direct application improved by the introduction of mycorrhizas.

2. The addition of mycorrhizas will sometimes give a big improvement in crop yield and in phosphate uptake from soil and/or rock. In other cases there will be no improvement, probably because the soil is already well infected in its own right.

3. The combination of phosphate rock and mycorrhizas will be most effective in soils of low phosphate status. For example, benefits may be expected when there is a change of land use to agriculture.

4. Additions of mycorrhizas will give the biggest proportionate improvements when the response curve to phosphate rock addition alone is still in the rising section.

5. It is probable that mycorrhizas work by adding to the capacity of the roots of the host plant to explore the soil volume for phosphate ions.

6. Mycorrhizal activity is favored by high temperatures rather than the lower ones encountered in temperate agriculture.

7. Some ores which are difficult or expensive to use in conventional fertilizer manufacture might be employed successfully for direct application with or without mycorrhizas.

There is very much to be done before mycorrhizas can be considered for the improvement of phosphate uptake by plants. If successful developments do emerge, they will probably have most application to the poorer soils of semitropical and tropical countries. These are soils which man will have to bring into use if famines such as those which have occurred in the Sahara-Sahel region are to be avoided in the future.

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