Use of Phosphate Mining Waste in Secondary Road Construction

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A pilot study was undertaken to provide alternate methods of rebuilding county and other secondary roads using phosphogypsum, a phosphate mining waste that is abundant in fertilizer-producing countries, as an aggregate and stabilizer. Current construction practice for some of these roads consists of mixing and further compacting the generally granular soil subgrade with fine-grained soils that are transported to the site. These mixtures tend to be largely affected by changes in the moisture regime. Several phosphogypsum-sand mixtures have been studied, mainly under California Bearing Ratio tests, as well as unconfined compression tests, to determine their engineering properties under different curing conditions, as well as to find useful design parameters. Both dihydrate and hemihydrate phosphogypsum were used throughout this investigation. Most of these mixtures yielded significant strength and bearing gains; however, some of them also became unstable when soaked. A rapid-curing cutback asphalt, RC-70, was added to the mixtures to decrease their moisture susceptibility. It was found that a very small percentage of RC-70 is required for specimens to develop such water resistance. Several alternatives that would perform acceptably when used in the construction of secondary roads are presented in this paper.

INTRODUCTION

Fertilizer producers throughout the world are becoming increasingly concerned about the proper disposal and possible use of the waste material that results from the production of phosphoric acid. Wet-process phosphoric acid is manufactured after mixing finely ground phosphate rock with phosphoric acid, sulfuric acid, and water to produce a slurry of phosphoric acid and a phosphogypsum by-product. Phosphogypsum (hydrated calcium sulfate) is then separated from the phosphoric acid (liquid) by filtration (*1*). The phosphogypsum by-product, discharged from the filter and slurried with water, is pumped to large stockpiles where it is allowed to disperse (*2*).

It is estimated that between 4.5 and 5.5 tons of phosphogypsum are generated per ton of phosphoric acid produced (*3*). An increasing demand for phosphoric acid has consequently enlarged phosphogypsum stockpiles throughout the world. In the State of Florida alone, the phosphate industry generates over 33 million tons of phosphogypsum each year, and its stockpiles have been estimated at over 400 million tons. Predictions indicate that this figure will rise to 1 billion tons by the year 2000 (*4*).

Although research that is focused on finding adequate uses of phosphogypsum has intensified in recent years and mixtures with potential application in the construction industry have been developed, no significant industrialized use of this waste material has been reported (*5, 6*). The lack of cost-effective techniques for the removal of chemical impurities and processing of phosphogypsum has previously precluded its use in the building products industry. However, there have been remarkable advances in these techniques that suggest its not too distant application (*5*).

A more immediate application of phosphogypsum is possible when no special processing is required for its engineering use. A typical example is in the construction of bases and subbases for major roads and even as a riding surface, when mixed with other adequate aggregates, for secondary roads. A recent study completed by Usmen and Moulton involved the construction and monitoring of road test sections with base courses that contained 5 percent lime, 20 to 65 percent fly ash, and 75 to 30 percent fine calcium sulfate (fluorogypsum) (*6*). These authors concluded that ". . . the results obtained so far indicate that these mixtures show very good promise for use in pozzolanic bases and subbases in secondary roads, and relatively large percentages of waste calcium sulfate can be successfully used in such mixture."

Other laboratory studies have reported 28-day, unconfined compressive strength values of over 1,500 psi for lime, fly ash, and phosphogypsum mixtures, (*1, 7*) and near 1,000 psi for cement, sand, and phosphogypsum mixtures with a cement content of up to 10 percent (*1, 8*). The same authors reported that these mixtures were not greatly affected by moisture changes. Although the first type of mixture mentioned contains as much as 95 percent waste materials (fly ash and phosphogypsum), fly ash may not be readily available near the phosphogypsum piles in the required large quantities. The large amount of cement required to achieve adequate strength for the second type of mixture mentioned also might preclude its application in some of the phosphate-producing countries.

This study was aimed at determining whether or not any beneficial gains could be obtained when mixing phosphogypsum with naturally occurring subgrade soils, in particular granular soils, to be used in secondary road construction. In some instances, additives were blended with these mixtures to reduce their moisture susceptibility or render them insensitive to moisture changes. These mixtures offer alternatives to common construction practices for secondary roads that consist of mixing and further compacting the generally granular soil subgrade with fine-grained, clay-like soils that are transported to the site. Phosphogypsum adds cohesion to granular soils and could very well replace the already scarce and relatively expensive fine-grained soils. Suitable sand-phosphogypsum mixtures would not only contribute to the improvement of the performance of secondary roads throughout central and northern Florida, where these materials were obtained, but throughout other parts of the world where similar conditions may be found. However, this is provided that environmental

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concerns regarding the use of phosphogypsum in this type of construction activity can be resolved. At the same time, a large step could be taken to partially solve the disposal problem of phosphogypsum, because large amounts of it may be required in these secondary roads.

Several phosphogypsum-sand mixtures were studied under California Bearing Ratio (CBR) tests, as well as unconfined compression tests, to determine their engineering properties under different curing conditions, as well as to find useful design parameters. Both dihydrate and hemihydrate phosphogypsum were used throughout the investigation. Most of these mixtures yielded significant strength and bearing gains; however, some of them also became unstable when soaked. In such cases, small amounts of a rapid-curing cutback asphalt were added to the mixtures to successfully reduce their moisture susceptibility.

MATERIALS

Phosphogypsum

Phosphogypsum, a waste product from the phosphate industry that primarily contains calcium sulfate, is a material mostly composed of fine particles that develops strength when compacted, but becomes unstable when saturated (*9*). Instability is unnoticed, however, when phosphogypsum of the hemihydrate type is soaked. The gypsum by-product, discharged from the filter and slurried with water, is pumped to large piles, where the final moisture content stabilizes to between 20 and 30 percent. The nature of the phosphate rock and the degree of digestion and filtration determine the chemical composition of phosphogypsum (*2*). A typical chemical analysis and pH range of a phosphogypsum sample are shown in Table 1. Calcium sulfate may be present in phosphogypsum in percentages as high as 95 percent; the remaining percentage consists of impurities such as silica, phosphates, fluorides, and organic constituents. Among the impurities is radium from the original ore that remains and coprecipitates with the calcium sulfate.

TABLE 1 TYPICAL CHEMICAL ANALYSIS OF PHOSPHOGYPSUM (FROM REF.7)

$CaSO_4.2H_2O$	85.0 - 95.0%
P_2O_5	0.2 - 1.7%
F	0.4 - 1.3%
SiO_2	1.4 - 8.4%
Soluble Salts	0.1 - 5.3%
pH	3.1 - 5.3

Crystals of calcium sulfate can exist in at least three forms: anhydrate ($CaSO_4$), hemihydrate ($CaSO_4 \cdot 1/_2H_2O$), also termed plaster of Paris, and dihydrate ($CaSO_4 \cdot 2H_2O$) (*1*). The phosphate industry generates either one of the last two types mentioned depending on the processes that were used to obtain phosphoric acid. Both types, obtained from different phosphate producing plants, were therefore used throughout the investigation.

The grain size of phosphogypsum depends on the processes used and the degree of grinding prior to the chemical reaction. The grain size distribution curves are shown in Figures 1 and 2, along with their specific gravities, for the dihydrate and hemihydrate phosphogypsum samples, respectively, used in the preparation of mixtures to be discussed later. The hemihydrate phosphogypsum is coarser and has a higher specific gravity than the dihydrate phosphogypsum. However, these relative characteristics may change, depending on the amount of impurities and the processing of the phosphate rock. Both types of phosphogypsum showed nonplastic characteristics.

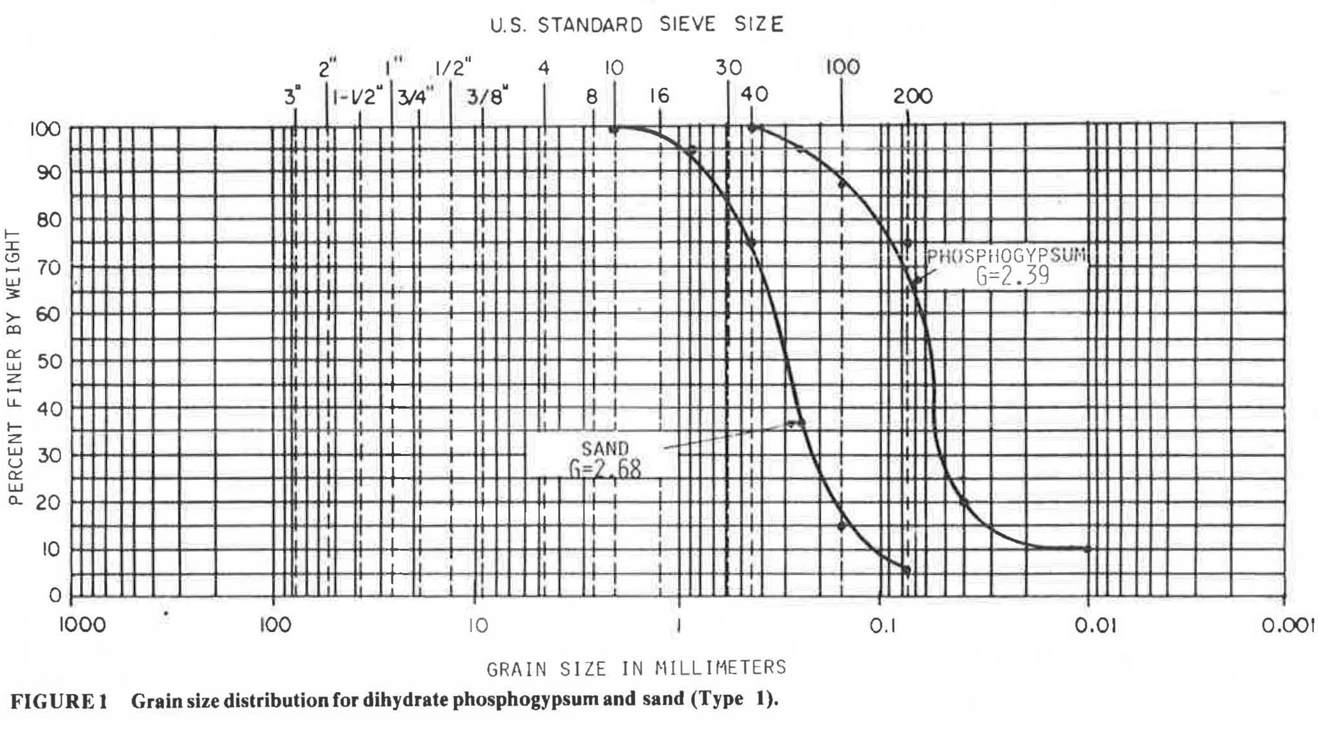

FIGURE 1 Grain size distribution for dihydrate phosphogypsum and sand (Type 1).

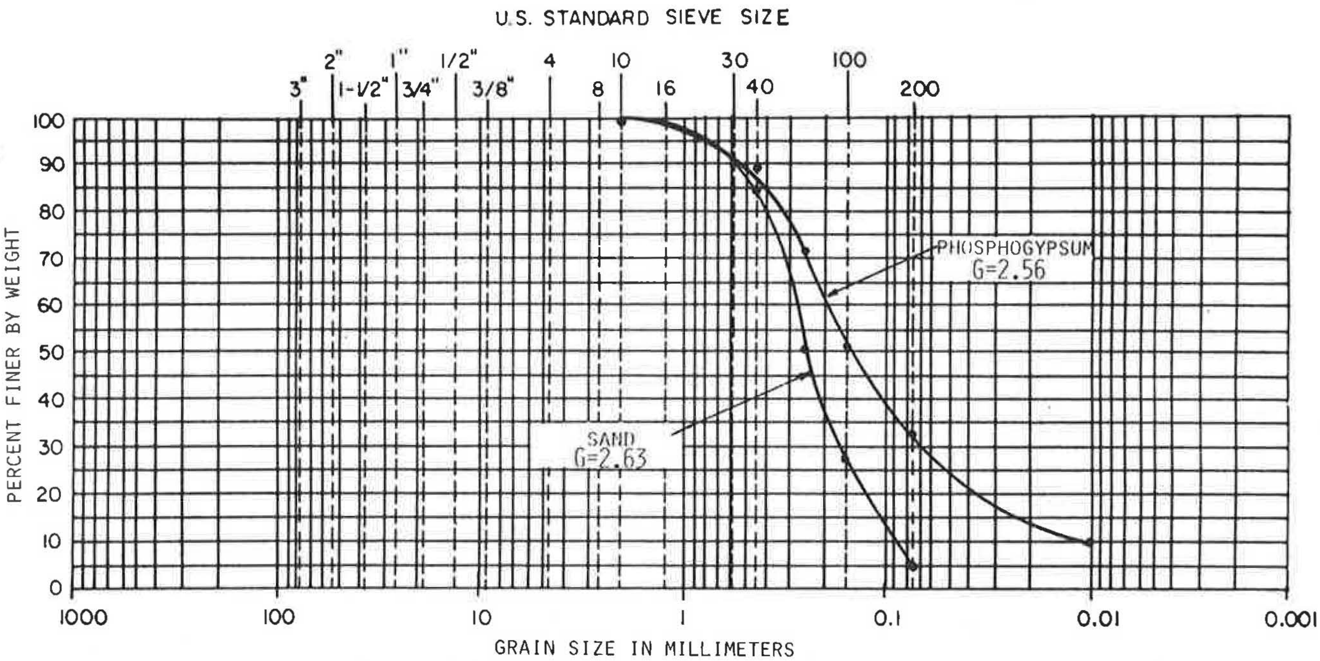

FIGURE 2 Grain size distribution for hemihydrate phosphogypsum and sand (Type 2).

Sand

Although sand samples were obtained from two different sources for the preparation of test specimens, they presented similar characteristics in regard to their grain size, classification, and composition. These soils could be considered typical within the counties where the phosphate rock processing plants are located. Both silica sands could be classified as A-3 soils (AASHTO Soil Classification System) and had a specific gravity of 2.68 and 2.63, respectively. The grain size distribution of each type of sand is presented in Figures 1 and 2 together with the curve of the corresponding type of phosphogypsum used in the preparation of mixtures.

Cutback Asphalt

A rapid-curing cutback asphalt (RC-70, which is an asphalt cement dissolved in highly volatile solvent with a low boiling point, such as naphtha or gasoline) was blended with sand-phosphogypsum mixtures in an attempt to reduce their moisture susceptibility. Other asphalt derivatives such as emulsions were also blended into the mixture; however, no satisfactory results were obtained with these types of additives.

SAMPLE PREPARATION AND TESTING

A total of six mixtures were used in the preparation of test specimens. Three of the mixtures contained dihydrate phosphogypsum and sand (Type 1) whereas the remaining three mixtures were prepared with hemihydrate phosphogypsum and sand (Type 2). Several proportions of sand and phosphogypsum were tested to determine the effect of the amount of phosphogypsum on properties of common use in compacted earthworks and to determine the relative percentages that led to the most desirable engineering properties.

The determination of the moisture content of samples containing phosphogypsum was conducted at 60°C for 24 hours to prevent the calcination of phosphogypsum. All moisture-density specimens exhibited an increased optimum moisture content with an increased amount of phosphogypsum.

Unsoaked laboratory and field CBR tests were used to evaluate the potential use of the selected mixtures as surface courses in secondary roads. Field CBR tests were performed on small pavement sections (3 ft × 3 ft × 5 in thick) compacted outdoors over an existing limerock base. These sections were exposed to periods of rain and dryness for several weeks before they were tested. In some instances, the field sections were flooded; however, most of the resulting mixtures exhibited very low permeability, which greatly prevented the penetration of water. Test sections were constructed next to each other, and no effort was made to vary the resulting moisture content after mixing appropriate amounts of phosphogypsum and sand directly from outdoor stockpiles. Laboratory specimens, however, were compacted below and above optimum moisture content to determine its effect on the CBR.

Small specimens 2 in in diameter and 4 in in length were also compacted following modified Proctor compaction specifications to obtain a measure of the relative strength of the mixtures shown in Table 2, and to determine whether or not strength development was time-dependent. These specimens were tightly wrapped in a plastic membrane immediately after preparation to prevent any moisture losses during the time preceding unconfined compression testing. Some of the specimens were soaked in water before they were tested to observe the quality of the bond between sand and phosphogypsum under submerged conditions.

Small amounts of RC-70 (up to 2 percent by dry weight) were added to some of the mixtures to improve the bond of the sand-phosphogypsum matrix. It was expected that such mixtures would behave in a favorable manner when subjected to a variable moisture regime.

TABLE 2 MIXTURE CHARACTERISTICS

Mixture No.	Dih. Gyps. (%)	Sand #1 (%)	Hem. Gyps. (%)	Sand #2 (%)	γ_D Max (pcf)	W_{OPT} (%)
1	25	75			119.1	6.2
2	33.3	66.6			126.4	8.7
3	50	50			120.1	9.4
4			33.3	66.6	122.9	7.0
5			50	50	126.0	9.0
6			66.6	33.3	129.1	9.8

RESULTS AND OBSERVATIONS

Moisture-Density Relationships

Values of the maximum dry unit weight and optimum moisture content, obtained through modified Proctor compaction testing, for each mixture are summarized in Table 2. Mixtures of dihydrate phosphogypsum and sand initially showed an increased maximum dry unit weight with an increased amount of phosphogypsum. However, the dry unit weight peaked and eventually decreased with an increased amount of phosphogypsum. Dihydrate phosphogypsum, which has a significantly lower specific gravity than Type 1 sand, initially fills the voids that exist between the generally uniform sand grains, and thereby increases the maximum dry unit weight. An excess of dihydrate phosphogypsum, however, leads to a reduced maximum dry unit weight.

Mixtures that contained hemihydrate phosphogypsum consistently showed an increased maximum dry unit weight with an increased amount of the waste material. Although hemihydrate phosphogypsum has a slightly lower specific gravity than Type 2 sand, increased amounts of this material produced a denser mixture. Total replacement of sand was avoided because it was considered necessary to obtain a mixture that contained coarse aggregate to partially reduce the possibility of slippery conditions when it was wet, and to reduce transportation costs, because the aggregate was already available at the construction site.

Laboratory and Field CBR

The results of unsoaked CBR tests of modified Proctor-compacted specimens agreed closely with the results of compaction tests. A maximum CBR value was generally obtained at a moisture content near optimum. Any increase in moisture beyond this level led to a sharp decrease in the CBR value. In addition, the sand-phosphogypsum (either dihydrate or hemihydrate) mixture with the highest maximum dry unit weight also indicated the highest CBR. Details of the variation of CBR with compaction moisture content for mixtures containing either dihydrate or hemihydrate phosphogypsum are presented in Figures 3 and 4, respectively. The type of mixture that led to the maximum CBR value also coincided with the type of mixture that led to the maximum dry unit weight. These results indicate the adequacy of moisture-density control during construction to secure adequate bearing characteristics from sand-phosphogypsum mixtures.

The addition of small amounts of RC-70 (1 to 2 percent by dry weight) to a sand-dihydrate phosphogypsum mixture did not produce any significant changes in the CBR-moisture

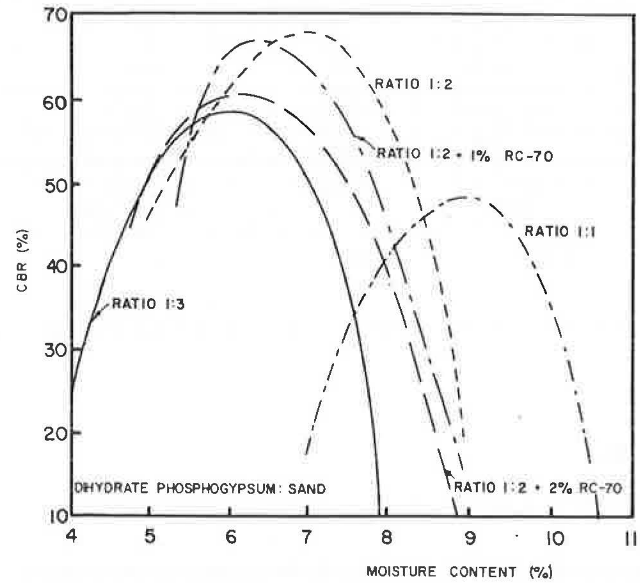

FIGURE 3 Effect of compaction moisture content on the CBR of dihydrate phosphogypsum-sand-RC-70 mixtures.

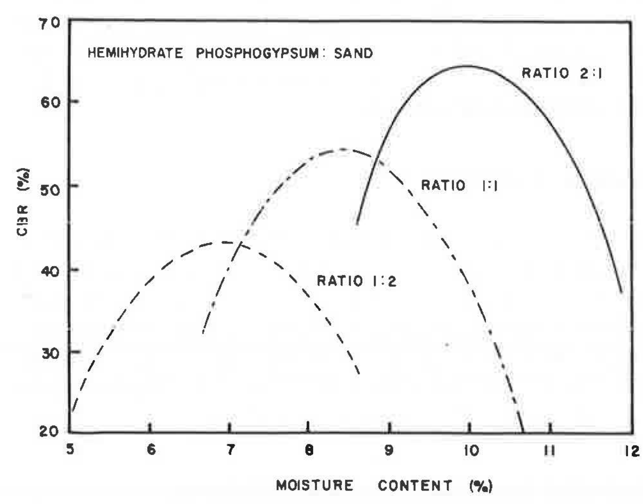

FIGURE 4 Effect of compaction moisture content on the CBR of hemihydrate phosphogypsum-sand mixtures.

content relationship, as shown in Figure 3. A slightly lower CBR was obtained when 2 percent, instead of 1 percent, of RC-70 was added to a mixture containing one part of dihydrate phosphogypsum and two parts of Type 1 sand. No cutback asphalt was added to hemihydrate phosphogypsum-based specimens, because it was found that they could withstand cyclic wetting and drying without collapsing because of the lasting bond introduced by this type of phosphogypsum.

A total of eight pavement sections were compacted outdoors with a mechanical compactor to obtain relative CBR values after several weeks of exposure to wetting and drying cycles. In all cases, the compaction moisture content was slightly higher than optimum (1 to 2 percentage points), which resulted from mixing adequate proportions of sand and phosphogypsum directly from outdoor stockpiles. The mixture compositions and the results of field and laboratory CBR tests are shown in Table 3. The addition of either type of phosphogypsum to sand was consistently beneficial in increasing the CBR. The section that contained 100 percent hemihydrate phosphogypsum, for all practical purposes, set as a rigid layer. The addition of cutback asphalt to the sand-dihydrate phosphogypsum mixture did not significantly improve the CBR. However, it was noticed that this pavement section was less prone to softening after rainy periods than the section without the cutback asphalt. Field CBR values were found to compare reasonably well with laboratory results.

Unconfined Compressive Strength

Unconfined compression testing was primarily used as a measure of the binding abilities of phosphogypsum. A comparative study was performed to determine whether or not there was a significant gain in the unconfined compressive strength, with time, of specimens containing both types of phosphogypsum. Specimens that were prepared under identical conditions, and at their optimum moisture content, were tightly wrapped to prevent loss of moisture and were allowed to cure at room temperature (78° F) for up to 3, 7, 14, 21, and 28 days before they were tested under unconfined compression.

All mixtures tested showed significant increases in their unconfined compressive strength with time, as shown in Figures 5 and 6, for mixtures containing dihydrate and hemihydrate phosphogypsum, respectively. Increases in strength were of a lower magnitude when the mixture contained cutback asphalt. The results of unconfined compression tests were also generally higher for mixtures that yielded higher maximum dry unit weights. The curves presented in Figures 5 and 6 represent the average of the test results of at least three specimens per curing time and for each type of mixture.

Finally, the effect of a variable moisture regime was investigated after subjecting the compacted specimens to cyclic

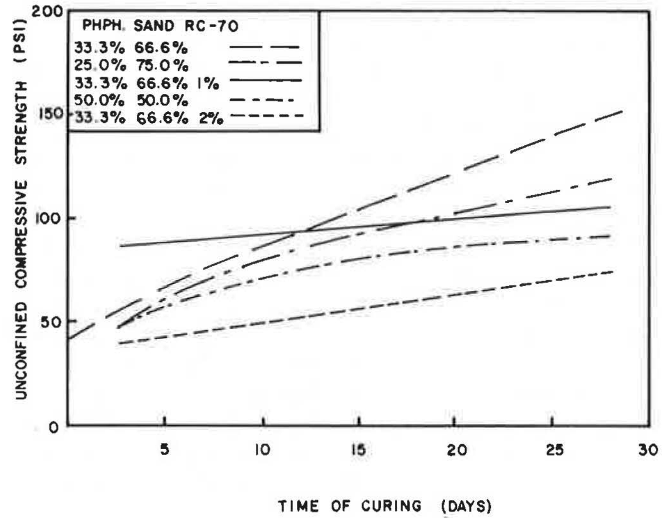

FIGURE 5 Effect of time of curing on the unconfined compressive strength of dihydrate phosphogypsum-sand-RC-70 mixtures.

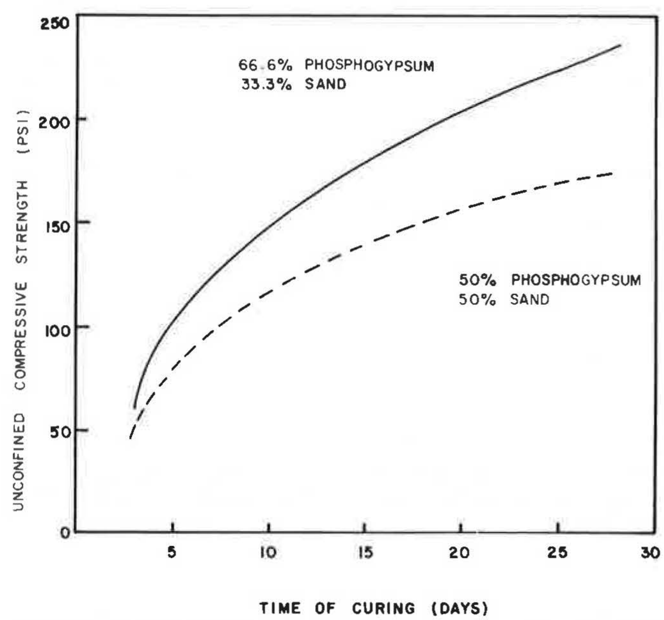

FIGURE 6 Effect of time of curing on the unconfined compressive strength of hemihydrate phosphogypsum-sand mixtures.

TABLE 3 VARIATION OF FIELD AND LABORATORY CBR WITH MIXTURE PROPORTIONS

Section No.	Dih.Gyps. (%)	Sand #1 (%)	Hem. Gyps. (%)	Sand #2 (%)	RC-70 (%)	CBR1 (%)	CBR2 (%)
1		100				28	
2	100					34	
3	33.3	66.6				66	68
4	32.6	65.4			2	75	61
5				100		29	
6			50	50		46	54
7			66.6	33.3		79	65
8			100			°100	

CBR1 = Field CBR
CBR2 = Laboratory CBR

wetting and drying. Each wetting cycle consisted of submerging the specimens in water at room temperature for 48 hours. The drying cycle, also of a 48-hour duration, consisted of subjecting specimens to a temperature of 60°C to prevent the calcination of phosphogypsum. The results of unconfined compression tests of mixtures that contained dihydrate phosphogypsum, sand, and 1 or 2 percent RC-70, as shown in Figure 7, indicated that although strength was lower after the wetting cycle, specimens remained bonded because of the influence of the asphalt cutback. Specimens without asphalt cutback collapsed during the first wetting cycle, which indicated the lack of a water-resistant bond between sand and dihydrate phosphogypsum. Specimens that contained hemihydrate phosphogypsum, however, developed a water-resistant bond that eliminated the need to add any waterproofing material. The effects of freezing and thawing were not examined because these problems did not typically occur in the geographical zones under consideration.

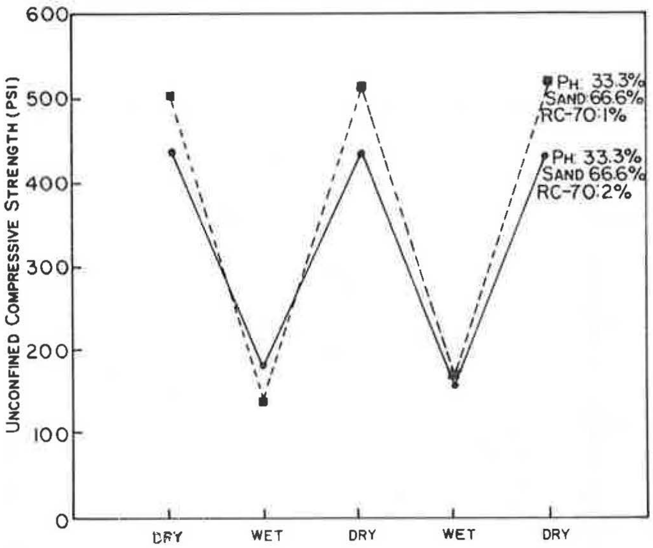

FIGURE 7 Effect of cyclic wetting and drying on the unconfined compressive strength of sand-dihydrate phosphogypsum-RC-70 mixtures.

DESIGN RECOMMENDATIONS AND CONCLUSIONS

Results of laboratory and field testing of phosphogypsum-based mixtures indicate that phosphogypsum promotes sand particle bonding, which in turn prevents surface erosion to some extent. A stronger, water-resistant bond develops between sand and hemihydrate phosphogypsum; however, a small amount of waterproofing material (1 to 2 percent RC-70) should be added when the mixture is prepared with dihydrate phosphogypsum, especially when this mixture will be subjected to a variable moisture regime.

A mixture that contains one part of dihydrate phosphogypsum and two parts of sand with 1 to 2 percent RC-70, and a mixture that contains two parts of hemihydrate phosphogypsum and one part of sand, each yield a CBR of over 60 percent (a little over twice the value of sand alone), which will definitely contribute to the improvement of surface conditions in low-volume road construction. Under these circumstances, a structural coefficient equal to 0.12 could be used to determine the required thickness of either one of the two types of phosphogypsum-stabilized surface layer, following the AASHO flexible pavement design procedure. This structural coefficient has been determined from known correlations with the CBR (*10*).

Two pavement sections, each over 1 mi long, have been recently built in central and northern Florida using selected mixtures of sand, phosphogypsum, and RC-70 as a result of this study. Initial observations indicate adequate structural and functional performance in both pavement sections; however, a longer observation period will be necessary before any definite conclusions can be drawn. Groundwater monitoring wells installed along both roads do not show any evidence of leaching to date. These encouraging results suggest the possibility of an imminent solution to two problems: how to improve the performance of secondary roads and how to properly dispose of a waste material.

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