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Related to
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**Construction Considerations in Naturally Occurring Asbestos Areas:
A Case Study**

Christopher G. Ward, Aileen C. Smith, and Karen Richardson

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Foreword

The nine papers in this volume are arranged into two groups. The first group consists of five papers on the application of cementitious stabilization technology for treatment, solidification or stabilization, and enhancement of materials in which environmental control is one of the primary objectives. Merritt et al. discuss applications of cement and soil chemistry to stabilization-solidification (S/S) technology. They examine the relative importance of kinetics and equilibrium of chemical processes in S/S technology. Martin et al. describe the results of a laboratory study that involved application of S/S technology to a hydrocarbon sludge contaminated clayey matrix. They also discuss the potential of such an approach to hydrocarbon-contaminated soils in highway rights of way. Taha presents physical and chemical characters, results of radiological and leachate analyses, and mechanical properties of flue gas desulfurization gypsum produced from power plants burning sulfur coals. Ong et al. describe the unconfined strength development of cement-stabilized phosphogypsum mixes that had different compacted densities, moisture contents, cement type and content, and curing procedure and time. Pamukcu and Tuncan present data on strength, permeability, and durability of a kiln slag, which contained metal iron and iron oxide around 30 percent by weight that was stabilized with cementitious materials.

The second group contains four papers on issues related to asbestos minerals that occur naturally in some metamorphic rocks. In a few areas these rocks contain significant percentages of asbestos minerals high enough to potentially affect human health if disturbed during construction or by other activities that could raise considerable volumes of airborne dust. The health dangers associated with exposure to airborne asbestos particles have resulted in stringent monitoring and control requirements by the Environmental Protection Agency and the Occupational Safety and Health Administration. These regulations were developed to protect persons exposed to asbestos materials in buildings, such as during renovation of older buildings containing asbestos insulation. Discussed in three of the four papers presented here is the extension of these regulations to construction in areas of naturally occurring asbestos. Dusek and Yetman present the issues from a regulator's viewpoint. Ward et al. describe the contractor's responsibilities, including worker education, health and safety issues, and monitoring and reporting requirements at a construction site located in a high-risk asbestos-bearing rock area. Rude relates these issues to a highway reconstruction situation and Huf and Stuart describe the results of a U.S. Forest Service study to estimate the extent of public exposure to airborne asbestos particles from aggregate used as road-surfacing materials. They measured asbestos emissions at several quarries operating in asbestos-bearing rocks and during travel along roads surfaced with such rock.

Applications of Soil and Cement Chemistry to Stabilization/Solidification

STANLEY D. MERRITT, BILL BATCHELOR, DALLAS N. LITTLE, AND
MICHAEL STILL

The main objective of waste stabilization/solidification (S/S) is to add binders to reduce the mobility of toxic contaminants. Immobilization can occur by either physical or chemical means. Physical immobilization occurs when the contaminant is encapsulated in a solid matrix. Chemical immobilization occurs when the contaminant is converted by chemical reaction to a less mobile form. Precipitation and adsorption are examples of chemical processes that can lead to immobilization. Physical processes in soil treatment have received the greatest attention with more data being collected on physical properties of the treated materials. The chemical processes associated with S/S have received less attention, particularly those processes that affect contaminants. Discussed in this paper are applications of cement and soil chemistry to S/S technology. The relative importance of kinetics and equilibrium of chemical immobilization in S/S are also examined. Equilibrium chemistry is presented as a practical method for describing how reactions between binders and soil produce the chemical environment that determines whether contaminants will exist in mobile or immobile forms. The use of chemical equilibrium models and programs such as SOLTEQ are discussed. SOLTEQ, a modification of an EPA-supported program (MINTEQA), can calculate concentrations of contaminants in both mobile and immobile phases and provides mechanisms to integrate chemical information from a variety of systems, including cementitious-pozzolanic systems such as soils or wastes by S/S. The importance of pozzolanic reactions to developing the chemical environment in wastes and soils treated by S/S is also discussed.

The goal of stabilization/solidification (S/S) technology applied to wastes is to contain contaminants and prevent them from moving into the environment (1). This goal is accomplished through the addition of additives to chemically bind and physically entrap contaminants in a solid. A secondary objective is the production of solids that are more manageable when disposed or used for some beneficial purpose (1-3). The use of S/S technology for soil treatment also has the goal of immobilization by chemical and physical means; however, the final result is often the creation of materials for construction or site remediation (4-6).

Application of S/S technology to soils requires that ample attention is paid to the system chemistry. System chemistry largely determines the ability of materials to resist leaching. Chemical reactions form compounds that determine the physical properties of treated materials. Therefore, it is essential that chemistry be considered. Economic constraints and re-

source availability will affect binder choice, but not how binders behave in treatment (7).

The most commonly used S/S processes use chemical reactions achieved by mixing cement, lime, fly ash, kiln dust, or combinations of these to effect pozzolanic reactions. These reactions can result in contaminant binding, liquid and sludge conversion into solid waste forms, and the development of engineering properties suitable for construction (2,4). Reviewed in this paper are combinations of cement and pozzolanic materials in soils. However, the results are also applicable to combinations involving fly ash and lime. The paper will include a discussion of the chemistry involved, the ability to model such systems, and preliminary results from applying the technology to the chemical immobilization of contaminated soils.

DEFINITIONS AND TERMINOLOGY

There are no "official" definition sets currently in the S/S area, but agencies such as ASTM and the Environmental Protection Agency (EPA) are either working toward this or have officially promulgated terminology (3). Unfortunately, there has been a tendency to use such words as chemical fixation, stabilization, and solidification interchangeably, although such terms have very distinct meanings when applied to S/S technology (3). Stabilization and solidification have been defined as follows (3,8):

Stabilization refers to those techniques that reduce the hazard potential of a waste by converting the contaminants into a less soluble, mobile, or toxic form. The physical nature and handling characteristics of the waste are not necessarily changed by stabilization.

Solidification refers to techniques that encapsulate the waste in a monolithic solid of high structural integrity. The encapsulation may be of fine waste particles or of a large block or container of waste. Solidification does not necessarily involve chemical interaction between wastes and solidifying reagents, but may mechanically bind the waste into the monolith.

It is important to note the difference in this definition of stabilization and the definition associated with treating soils to improve mechanical properties. To avoid confusion, the term "chemical immobilization" will be used in this paper in place of "stabilization" as previously defined and the term "soil strengthening" in place of "stabilization" as used to denote processes of improving soil mechanical properties.

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PHYSICAL IMMOBILIZATION AND PHYSICAL PROPERTIES

Physical processes in S/S have received the greatest attention and thus most of the data available describe physical properties of treated materials. Physical immobilization is accomplished through the encapsulation of toxic materials or waste agglomerates with binders (1). If encapsulation is the only mechanism holding a contaminant, the degree of environmental protection is strongly based on the physical integrity and durability of the treated materials (3).

Common examples of measurements often conducted on samples are plasticity index, unconfined compressive strength, shrinkage/swell potential, freeze/thaw durability, and moisture susceptibility. These types of measurements are typically used to reflect changes in physical properties of treated materials; however, they are not very useful for predicting whether contaminants will leach from treated materials. If a S/S treatment is to be considered successful from an environmental standpoint, data must reflect how much material could leach from the S/S form in the short and long term.

CHEMICAL IMMOBILIZATION

The ability to chemically immobilize material is an important aspect of S/S technology because of its strong impact on the level of contaminant mobility. Furthermore, chemical reactions determine properties of treated materials that are important to their use as construction materials.

Chemical binding requires that some reactions occur before desired pozzolanic or cementitious reactions, or both, take place. In soil systems treated by lime or cement, the reactions that must occur are hydration, cation exchange, flocculation, and agglomeration. Hydration processes provide necessary means to increase soluble ionic concentrations. When cement hydrates or lime ionizes in water, the dissolved concentrations of calcium and hydroxide ions are initially increased because calcium hydroxide is released either from calcium silicates as they hydrate (9,10) or directly from added lime (4). The increase in hydroxide ions produced by hydration also increases the pH of the solution. These initial reactions are typically completed within a few hours.

After initial reactions, pozzolanic or cementitious reactions, or both, can take place. It is important in soil strengthening to differentiate between cementitious and pozzolanic reactions (9). Cementitious reactions refer to the hydration reactions that occur when calcium silicates and calcium aluminates combine with water to form calcium-silicate-hydrate (CSH) and calcium-aluminate-hydrate (CAH) reaction products. Pozzolanic reactions are reactions among alkaline earth elements, such as calcium, and reactive siliceous materials with high surface areas, such as clays. If clay is strengthened by cement hydration, this reaction may simply "cement" grains or clods of clay together without penetrating into the clay and affecting the clay mineralogy. However, if pozzolanic reactions occur, physical properties of the clay are often altered considerably, because the clay is actually "attacked" as it reacts. Changes in clay mineralogy have been well documented as a result of pozzolanic reactivity through scanning electron microscopy and X-ray diffraction (11,12). Both these reactions are time- and temperature-dependent and can con-

tinue to affect properties of treated materials years after initial treatment.

Precipitation reactions convert mobile forms of contaminants into immobile solids. High-pH environments in chemically immobilized systems often lead to the formation of metal-hydroxide precipitates (3), but metal-silicate, carbonate, and sulfate precipitates also are formed (3,13).

MODELING OF SYSTEMS

The complexity of modeling leaching of contaminants from materials treated by S/S is the result of the combination of physical and chemical factors that exists. However, simple leach models can be used to demonstrate leaching relationships using these factors, even when they are not useful in predicting leaching.

The simplest leach models assume that treated solids are semi-infinite slabs of rectangular geometry contained within well mixed, infinite baths (14). The material balance equation and its initial and boundary conditions are (14)

$$\frac{\partial C}{\partial t} = D_e \frac{\partial^2 C}{\partial X^2} - R \quad (1)$$

Initial Condition: $C = C_0$ at $t = 0$, all X

Boundary Conditions: $C = 0$, at $X = 0$, all t

$C \rightarrow C_0$ as $X \rightarrow \infty$

where

- C = mobile component concentration,
- C_0 = mobile component concentration at time zero,
- t = time,
- D_e = effective diffusivity,
- X = distance into solid, and
- R = removal rate of mobile component from solution per volume of total solid.

This mass balance is applicable for any system with transport in one direction whether infinite or not.

When the general mass balance is constrained with the assumptions of (a) no reactions, (b) infinite baths, (c) semi-infinite slab, and (d) homogeneous solid, this system can be solved to give the following relationship for the fraction of contaminant leached (14):

$$\frac{M_t}{M_0} = \left(\frac{4D_e}{\pi L^2} \right)^{0.5} t^{0.5} \quad (2)$$

where

- M_t = component mass leached at time = t ,
- M_0 = component mass in solid at time = 0, and
- L = distance from center of slab to surface.

The semi-infinite slab assumption can limit this model when the fraction leached is moderately high (i.e., $M_t/M_0 > 0.20$). Care must therefore be taken when using this equation.

The systems of most interest are those in which chemicals do react. The effect of simple reactions can be described easily

if the reactions are assumed to be in equilibrium (14). This is normally a good assumption because the time required for reaction is generally smaller than that required for transport out of the waste form (14). Leaching equations can be shown to have the same form as Equation 2 for numerous simple reactions, but the equation contains an observed diffusivity rather than an effective diffusivity (14-16).

$$\frac{M_t}{M_0} = \left(\frac{4D_{\text{obs}}}{\pi L^2} \right)^{0.5} t^{0.5} \quad (3)$$

The definition of observed diffusivity depends on the assumed chemical and physical reactions.

$$D_{\text{obs}} = \frac{D_m}{f_c \times f_p} \quad (4)$$

where

D_{obs} = diffusivity observed from the effect of chemical and physical mechanisms,

D_m = molecular diffusivity,

f_c = factor describing chemical immobilization, and

f_p = factor describing physical immobilization.

The physical factor (f_p) is the ratio of molecular diffusivity to effective diffusivity and has been defined as the MacMullin number (15,17).

$$D_{\text{obs}} = \frac{D_m}{N_M \times f_c} \quad (5)$$

where N_M is the MacMullin number.

N_M can be determined by a technique based on electrical conductivity measurements (15). Transport of ions by either diffusion or electrical field is affected in the same way by the structure of a porous solid; therefore, measurement of solid and pore water conductivity can be used to calculate the effective diffusivity of a compound within the solid (15). N_M can be calculated as the ratio of pore water conductivity to solid conductivity.

The chemical factor (f_c) depends on the type of reactions assumed. If linear sorption is assumed, the observed diffusivity is defined (14,16)

$$D_{\text{obs}} = \frac{D_e}{1 + K_p} = F_m D_e = \frac{D_m}{(N_m)(1 + K_p)} \quad (6)$$

$$f_c = (1 + K_p) \quad (7)$$

where K_p is the linear partition coefficient, equal to ratio of sorbed phase concentration to solution phase concentration at equilibrium and F_m is the contaminant fraction initially mobile.

If a portion of the contaminant is assumed to have reversibly precipitated, the following definition applies (14):

$$D_{\text{obs}} = \frac{\pi[F_m(1 - F_m) + 0.5F_m^2]D_e}{2} = \frac{D_m\pi[F_m(1 - F_m) + 0.5F_m^2]}{N_M \times 2} \quad (8)$$

$$f_c = \left(\frac{2}{\pi[F_m(1 - F_m) + 0.5F_m^2]} \right) \quad (9)$$

If the fraction of contaminant in the mobile phase is small, this reduces to the following (14):

$$D_{\text{obs}} = \frac{\pi F_m D_e}{2} = \frac{D_m \pi F_m}{N_M \times 2} \quad (10)$$

$$f_c = \left(\frac{2}{\pi F_m} \right) \quad (11)$$

These simple leach models demonstrate the importance of observed diffusivity on the ultimate leachability of an S/S material. The equations presented show how observed diffusivity is highly dependent on physical and chemical factors. The relative importance of the chemical factor is dependent on the contaminants involved, and this is reflected in measured values of observed diffusivity. Observed diffusivities for several contaminants are shown in Table 1. The table shows that different contaminants are immobilized to widely different degrees in the same solidified waste (15), and, because the data were obtained from the same waste form, all differences in observed diffusivity can be attributed to chemical factors. A small observed diffusivity (i.e., a large $-\log D_{\text{obs}}$) represents a high degree of immobilization. Thus, those contaminants that should be relatively nonreactive, such as sodium, have the highest D_{obs} , and more reactive contaminants, such as lead, have the lowest D_{obs} .

The similarity of molecular diffusivity for several substances in a water medium is shown in Table 2. Values of molecular diffusivity have been measured for numerous compounds and can be estimated for numerous others (15,17,18). However,

TABLE 1 Reported Values of the Leachability Index ($-\log D_{\text{obs}}$) for Various Contaminants (15)

Contaminant	$-\log D_{\text{obs}}$ (m ² /s)
Na	12.3
Phenol	13.5
Nitrate	14.7
As	15.9
Cr	17.2
Pb	19.4

TABLE 2 Reported Values of Molecular Diffusivity in Water (17,18)

Substance	$-\log D_m$ (m ² /s)
Ethanol	8.92
Glucose	9.16
Acetone	8.89
Propan-2-ol	8.96
Chloride	8.82
CO ₂	8.70
O ₂	8.62
N ₂	8.59

when molecular diffusivity is measured for different substances in a similar medium, there is little difference in the values obtained.

Because molecular diffusivity varies little, the only factors that can influence the fraction of mobile contaminants are chemical and physical. Shown in Table 3 is N_M for several water/cement (w/c) ratios and for several levels of a silica fume admixture. These data show how N_M can vary with w/c ratios, curing time (17), and levels of admixtures (19).

The simple leach models are based on assuming simple reactions of one or two components. Chemical reactions in materials treated by S/S are much more complex. Many components are present and they can react in many ways. However, it is reasonable to assume that these reactions react relatively fast when compared with leaching so that chemical equilibrium is achieved. Currently, a chemical equilibrium model (SOLTEQ), which is a modification of an EPA-supported program (MINTEQA), is being used to predict chemical equilibrium that exists in S/S waste forms (14).

SOLTEQ can be used to estimate the fraction of contaminant in the mobile phase, F_m (14). As shown by Equations 9 and 10, the mobile fraction can be used to calculate observed diffusivity for simple one-component systems (14). However, this approach is quite limited because it ignores multicomponent chemical interactions.

SOLTEQ can also be used to predict the effect of multicomponent chemical interactions on leaching (14). The material balance equation presented for a nonreactive component, Equation 1, must be modified to consider a component that can exist in a number of different forms (14). The accumulation term must consider total concentration, and the transport term only considers mobile phase concentration (14). Because all reactions are conversions among species of the same component, the rate term is irrelevant and the material balance equation becomes the following (14):

$$\frac{\partial T_i}{\partial t} = D_c \frac{\partial^2 C_{m,i}}{\partial X^2} \quad (12)$$

TABLE 3 Reported Values of MacMullin Number (N_M) after 90 Days of Curing (17,19)

w/b Ratio b = Cement	N_M
0.40	207
0.50	171
0.60	97
0.80	54
1.00	27
<hr/>	
w/b Ratio = 0.5 b = Cement + Silica Fume	
Cement to Silica Fume Ratio (Weight % : Weight %)	N_M
95 : 5	201
90 : 10	356
85 : 15	373
80 : 20	476
75 : 25	631

where T_i is the total concentration of component i , and $C_{m,i}$ is the concentration of component i in all its mobile forms.

This equation can be solved simultaneously for numerous components by numerical techniques (14,20).

SOLTEQ provides a general multicomponent model to describe equilibrium partitioning of binder and waste components. It contains a thermodynamic data base with data for some compounds and pore water conditions often found in treated waste (14). However, SOLTEQ is limited by insufficient thermodynamic data for solid species not commonly found in cementitious forms, the phase rule for solid formation, and the heterogeneous mineralogy of waste forms encountered (14).

APPLICATION OF S/S TECHNOLOGY TO CONTAMINATED SOILS

The focus of soil strengthening has been on benefits achieved in the physical or engineering properties of the treated soil. Common physical properties examined before, during, and years after treatment are of limited importance to ultimate leachability. Therefore, when S/S technology is applied to contaminated soils, the focus should turn to those properties affecting leachability, such as soil pH, diffusivity, and the durability of the solid.

Soil pH is probably the single most important factor in determining the extent of chemical immobilization of contaminants. For applications of soil strengthening, the primary reason for measuring soil pH is to ensure that sufficient lime has been added to drive strength-producing reactions (4). A soil pH of 12.4 is typically used to indicate the presence of excess lime needed to drive pozzolanic reactions. However, reaching this pH does not ensure adequate performance, because it does not establish whether the soil will react with lime to produce a substantial strength gain; therefore, a strength test is necessary to show strength increases. Conventional techniques for measuring soil pH rely on mixing distilled water with a soil sample and measuring the pH of the resulting extract. This procedure is adequate for measuring pH in soil solutions equilibrated with lime, because lime particles can dissolve in the added water to maintain a pH near 12.4. However, this procedure will not likely be suitable when the pH of the soil water is controlled by a set of reactions more complex than the simple dissolution of lime.

Because pore water pH is directly related to the leachability of treated materials, a more accurate procedure is needed to measure the pH. A device has been developed to extract pore water from cured samples so that the hydroxide concentration of the pore water can be measured directly by titration (17,21). Pore water hydroxide concentrations can be used to accurately determine pH by calculation.

Research Plan

Because of the importance of soil pH to chemical immobilization, an experimental plan was developed to evaluate a pore water extraction method for measuring pore water hydroxide ion concentration. Experiments were conducted to evaluate effects of mix design and curing time on pore water hydroxide

TABLE 4 Mix Design for Cement-Simulated Soil Mixtures

Series	Cement - Simulated Soil Mixture					
	Simulated Soil		% Cement	% Water	% Clay % Cement	Mass Ratio of Simulated Soil : Cement
	% Sand	% Clay				
1	50.0	2.6	22.6	24.8	0.12	7 : 3
2	34.0	6.0	17.1	42.9	0.35	7 : 3
3	24.2	8.1	13.8	53.9	0.59	7 : 3
4	17.5	9.5	11.6	61.4	0.82	7 : 3
5	10.9	10.9	9.3	68.9	1.17	7 : 3

concentration and the amount of hydroxide per total amount of mixture. Mix designs used in experimentation were chosen to maintain constant mass ratio of simulated soil to cement. Shown in Table 4 are the percentages of components on the basis of total mass of material mixed. Nine replicate samples were prepared for each series with three replicates analyzed on each sampling. Specimens were cured at room temperature under lime water. The hydroxide ion concentration was determined through acid-base titration of expressed pore water to an endpoint of pH 7.

Methods

Samples were prepared by mixing Type I portland cement, sodium bentonite clay, and a 30-mesh sand with appropriate amounts of distilled water so that mixtures set sufficiently to prevent bleeding. Portions were then transferred to plastic concrete molds (50 mm × 100 mm), placed in a tumbler for 24 hr, and then placed in plastic bags under lime water to cure for the specified times. After curing, pore water was expressed from samples by using a pore water expression device (17,21). A schematic of the device is shown in Figure 1.

The pH of the expressed pore water was measured with a pH meter, Fisher 925, and then titrated with a sulfuric acid solution to an endpoint of pH 7.

Discussion of Results

Pore water hydroxide ion concentration versus the percentage clay content at different curing times is shown in Figure 2. The hydroxide ion concentration varies slightly with the percentage clay content. However, the curing time and the percentage clay content appear to affect hydroxide concentration, especially between 14 and 28 days of curing. The lack of initial change in pore water hydroxide concentrations has been noted elsewhere (9); however, upward trends exhibited with higher percentages of clay may be atypical of cement curing. These upward trends could be a result of not curing long enough to reach an equilibrium condition.

The amount of hydroxide ions per total mass of mixture versus the percentage clay content varied with time is shown in Figure 3. The results in Figure 3 show a trend similar to that in Figure 2. However, a more pronounced reduction in the amount hydroxide present as clay content is increased when measured after 7 days of curing is shown in Figure 3.

SUMMARY

The importance of leachability to the development of an environmentally sound S/S waste form cannot be overstated. Because of its importance, the chemistry of S/S will be very important to the application of S/S technology to contaminated soils. Knowledge and experience gained from dealing with waste S/S can be combined with that of soil strengthening to treat contaminated soils so that they are environmentally and structurally sound for many years. In particular, models for leaching and equilibrium chemistry and characterization techniques for pore water analysis and MacMullin number can be applied to soil treatment.

The application of S/S to contaminated soils will also be beneficial because of the relatively low cost of treatment and the ability to create a more easily workable soil for final disposal or in situ encapsulation at a waste site.

As more data from laboratory experiments and field demonstrations are collected on S/S of contaminated soils, the

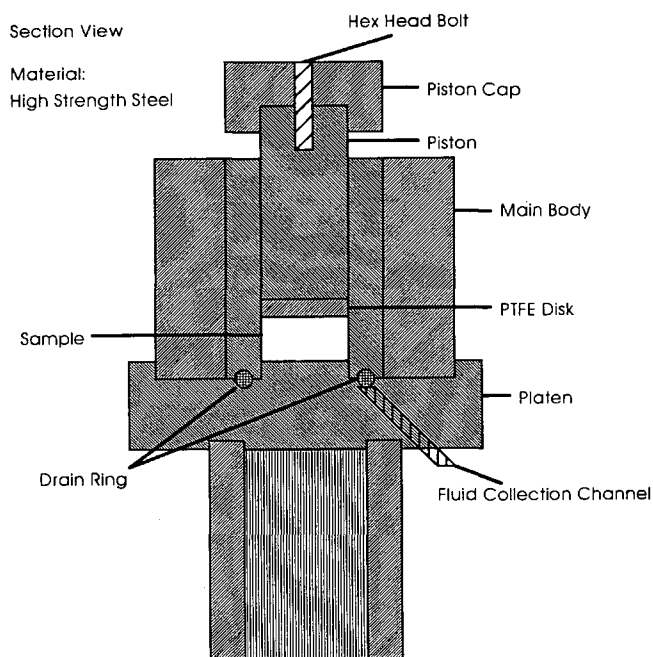


FIGURE 1 Schematic of pore water expression device.

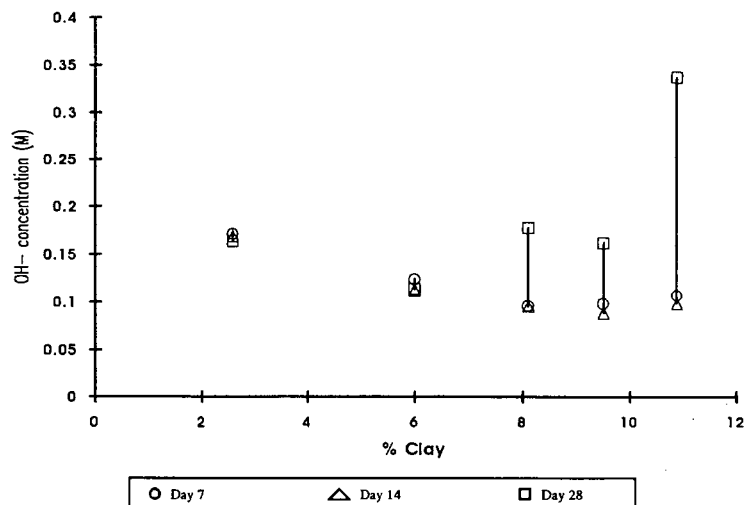


FIGURE 2 Hydroxide ion concentration versus percent clay content at different curing times.

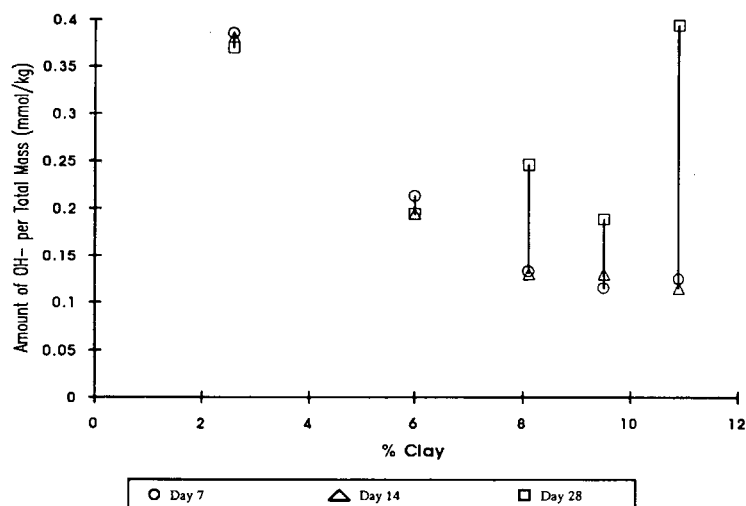


FIGURE 3 Amount of hydroxide ions per total mass of mix versus percent clay content at different curing times.

chemistry of such systems will be more fully understood, and questions about long-term leachability will be better addressed.

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REFERENCES

1. Evaluation of Solidification/Stabilization for Treating Hazardous Waste in the United States. In *Hazardous Waste: Detection, Control, Treatment, Part B*, (C. C. Wiles and R. Abbou, eds.), 1988, pp. 1525-1537.
2. Bishop, P. L. Leaching of Inorganic Hazardous Constituents from Stabilized/Solidified Hazardous Wastes. *Hazardous Waste & Hazardous Materials*, Vol. 5, No. 2, 1988, pp. 129-143.
3. Conner, J. R. *Chemical Fixation and Solidification of Hazardous Wastes*. Van Nostrand Reinhold, New York, 1990.
4. Lime Stabilization, Reactions, Properties, Design, and Construction. In *State-of-the Art Report 5*, TRB, National Research Council, Washington, D.C., 1987, pp. 3-34.
5. Barth, E. F. Summary of Solidification/Stabilization SITE Demonstrations at Uncontrolled Hazardous Waste Sites. *Stabilization and Solidification of Hazardous, Radioactive, and Mixed Wastes*, vol. 2. ASTM STP 1123, (T. M. Gilliam and C. C. Wiles, eds.), American Society for Testing and Materials, Philadelphia, Pa., 1992, pp. 409-414.

6. Little, D. N., M. R. Thompson, R. L. Terrell, J. A. Epps, and E. J. Barenberg. *Soil Stabilization of Roadways and Air Fields*, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Fla. 1987.
7. Poon, C. S. A Critical Review of Evaluation Procedures for Stabilization/Solidification Processes. *Environmental Aspects of Stabilization and Solidification of Hazardous and Radioactive Wastes*, ASTM STP 1033, (P. L. Côté and T. M. Gilliam, eds.), American Society for Testing and Materials, Philadelphia, Pa., 1989, pp. 114–124.
8. Cullinane, Jr., M. J., P. G. Malone, and L. W. Jones. *Handbook for Stabilization/Solidification of Hazardous Waste*. Environmental Protection Agency, Cincinnati, Ohio, 1986.
9. Herzog, A., and J. K. Mitchell. Reactions Accompanying Stabilization of Clay with Cement. In *Highway Research Record 36*, HRB, National Research Council, Washington, D.C., 1963, pp. 146–171.
10. Taylor, H. F. W. Hydrated Calcium Silicates, Part I, Compound Formation at Ordinary Temperatures. *Journal of American Ceramics Society*, 1950, pp. 3682–3690.
11. Little, D. N., and T. Petry. Effect of Sulfates on the Rate of Reaction of Lime-Stabilized Clay. Presented to the Materials Division of ASCE, July 1992.
12. Ferris, G. A., J. L. Eades, G. H. McClellan, and R. E. Graves. Improved Characteristics in Sulfate Soils Treated with Barium Compounds Before Lime Stabilization. In *Transportation Research Record 1295*, TRB, National Research Council, Washington, D.C., 1991, pp. 45–51.
13. Snoeyink, V. L., and D. Jenkins. *Water Chemistry*. John Wiley and Sons, New York, 1980, pp. 243–298.
14. Batchelor, B., and K. Wu. Effects of Equilibrium Chemistry on Leaching of Contaminants from Stabilized/Solidified Wastes. In *Chemistry and Microstructure of Solidified Waste Forms*, (R. D. Spence, ed.), CRC Press, Inc., Boca Raton, Fla., in press.
15. Batchelor, B. Leach Models: Theory and Application. *Journal of Hazardous Materials*, Vol. 24, 1990, pp. 255–266.
16. Batchelor, B. Modeling Chemical and Physical Processes in Leaching Solidified Wastes. In *Third International Conference on New Frontiers for Hazardous Waste Management*, EPA/600/9-89-072, Environmental Protection Agency, 1989.
17. Taffinder, G. G., and B. Batchelor. Measurement of Effective Diffusivities in Solidified Wastes. *Journal of Environmental Engineering*, in press.
18. Incropera, F. P., and D. P. DeWitt. *Fundamentals of Heat and Mass Transfer*, Second Edition. John Wiley and Sons, Inc., New York, 1985, p. 777.
19. Kyi, A. A. *The Effects of Additives on Effective Diffusivities in Solidified/Stabilized Wastes*. M.S. thesis, Texas A&M University, Texas, Aug. 1992.
20. Batchelor, B. A Numerical Leaching Model for Solidified/Stabilized Wastes. *Water Science Technology*, Vol. 26, No. 1–2, 1992, pp. 107–115.
21. Barney, R. S., and S. Diamond. Expression of Pore Fluids from Hardened Cement Paste and Mortars. *Cement and Concrete Research*, Vol. 11, No. 2, 1981, pp. 279–285.

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Solidification/Stabilization of Refinery Sludge in a Pozzolan-Cemented Clay Matrix

J. P. MARTIN, S. C. CHENG, AND P. A. FRY

A project involved solidification/stabilization of a hydrocarbon sludge in a silty clay matrix cemented with a pozzolanic lime-fly ash admixture. The compactable mixture can harden as a dimensionally stable landfill monolith that minimizes contaminant mobility. The solidification/stabilization product has more than 50 percent porosity to contain the sludge in the available airspace. This limits the strength to that of a firm cohesive soil, and mass behavior is evaluated by traditional geotechnical methods. Customary influences on fine soil permeability apply as well, with compactive effort alone affecting results over a range from 10^{-5} to 10^{-7} cm/sec. The solidification/stabilization process retards hydrocarbon mobilization primarily by physical microencapsulation. Less than 5 percent of the carbon was mobilized in 10-pore volumes of throughput in column leaching tests. This solidification/stabilization method appears to be suitable to allow reuse of the surface for industrial purposes as long as cap integrity is maintained. Consequently, the potential use of cemented clay solidification/stabilization for hydrocarbon-contaminated soils in highway rights of way is also indicated.

Many highway projects encounter soil contaminated with petroleum products in the right of way. Time and land use constraints often limit in situ remediation options, so excavation and offsite landfilling is a common solution even though only a fraction of the mass is the contaminant, and excavated soil must be replaced. An alternative method combines traditional soil stabilization with additives (1) and waste solidification/stabilization (S/S) methods (2), for treatment and redeposition under the roadway, as shown in Figure 1. S/S processes can be optimized for mechanical properties and the pavement section performs the same functions as a landfill cap: isolation of its subgrade from the surface environment.

S/S often uses cements and inexpensive byproducts as reactants to mechanically improve waste materials and immobilize contaminants (2-4). However, S/S may appear to be inappropriate for organic materials because they often interfere with hydration (5). Also, regulations often specify arbitrary values of material properties such as an unconfined compressive strength of 340 kN/m² or 50 psi (6,7), but lower strengths are certainly capable of bearing loads.

Treatment and onsite redeposition in capped landfill monoliths can be thought of as an extreme case of an organic conventional highway subgrade stabilization. Ground modification to meet deformation criteria for pavements is similar

to providing mechanical support to maintain the integrity of the landfill cap. Analysis of the S/S product response to the in situ environment is the appropriate approach (8). Cap surfaces settle and distort because of post-closure compression of the treated waste, which depends on both the gravity (self-weight) loads and the material compressibility, shown conceptually in Figure 2.

PROJECT DESCRIPTION

Acidic hydrocarbon sludges from petroleum processing have been stored in lagoons for several decades. Although little impact has been detected, permanent disposal was desired. Studies indicated that recycling, biodegradation, incineration, or offsite disposal were all unfeasible for technical, economic, or social impact reasons. S/S and onsite landfill deposition was seen as a viable alternative. A potential additional benefit is that the former lagoon "footprints" could be reclaimed for light industrial use.

Sequential pit-by-pit remediation was desired to allow adjustments to variations in sludge consistency variations, and to preserve the existing surface drainage system. The "air space" above the sludge surface in each lagoon is roughly equal to the sludge volume, so a maximum volumetric swell of 100 percent is allowed. Assuming that the sludge would be encapsulated without contributing to mechanical strength, this can be expressed as a requirement that the S/S product have an oil-filled volumetric fraction of at least 50 percent.

In a laboratory investigation, S/S with portland cement or lime-fly ash mixtures (4) at this porosity gave unsatisfactory results, barely meeting self-support and freely expelling the sludge liquid. Codisposal of the sludge with a very plastic spent clay (absorbent from refining operations) showed promising results, but the spent clay was difficult to handle. With the feasibility of using a fine-grained soil "skeleton" to encapsulate the sludge, S/S with the local clayey silt and a pozzolanic lime-fly ash additive was studied. Hardened samples display self-support, low permeability and favorable leaching results. The geotechnical properties of the stabilized mixture are comparable to that of a compacted clayey silt, so it is inferred that the admixture compensates for weakening effects of remolding and high porosity. Optimization of the proportioning, mixing method, and deposition technique is described elsewhere (8-10).

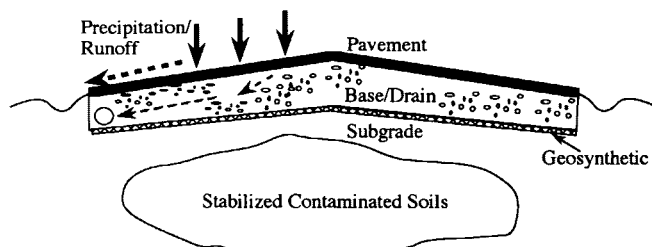


FIGURE 1 Treated soil burial under subgrade.

Monolith Performance

The ultimate goal of the stabilization component of S/S is to minimize transport of contaminants from the deposited mass. Contaminant movement requires three elements:

1. The contaminant must be mobile, in erodible particle, vapor, free liquid, or solute form;
2. There must be a pathway for movement; and
3. There must be a gradient to induce and sustain transport.

The engineering problem is to restrict these elements by a combination of S/S and external containment. The latter, as in conventional landfills, isolates the mass from surrounding surface and subsurface environments. The solidification component of S/S, especially the pore structure microencapsulation, restricts internal transport by mechanical means (i.e., it fosters resistance to deterioration, distortion, and seepage effects of the internal mechanical, hydraulic, and biochemical environment shown in Figure 2).

The internal pathway for seepage advection is often indexed by the saturated permeability. If the deposit is unsaturated, the effective permeability to liquids is lower still, but the ease of vapor movement is increased. Optimization of pathway restriction might involve having a degree of saturation in which the pair pores are occluded.

Some transport restrictions cannot be affected by S/S. It does not restrict hydraulic gradients, so the cap must shed rainfall to keep infiltration and seepage gradients intermittent

and limited. Concentration gradients driving diffusion are not controllable at all. Other concerns such as durability and erodibility are problematical, as a cemented oily clay does not resist freeze-thaw or wet-dry cycling or erosion. A thick, impermeable cap is necessary for climatic isolation. Matrix deterioration by biodegradation was not studied, although restriction of oxygen penetration and a high pH should retard aerobic activity.

Slope stability and bearing capacity (for vehicles) analyses show generous factors for safety at unconfined compressive strengths well below 100 kN/m² (15 psi). Consolidation indexes are the more relevant mechanical properties. For the site monoliths up to 15 m thick, the maximum overburden pressure anticipated is about 250 kN/m². The strain in the lower portion (Figure 2) caused by primary consolidation is computed to be about 5 to 6 percent. A similar amount of secondary consolidation over 50 years is expected (11). It is also desirable that the mixture be unsaturated to complete primary consolidation before cap installation and to minimize liquid expulsion.

Materials

Sludge

The sludge was deposited over several decades, during which there were process changes and ongoing volatilization and separation of the heavier fractions, resulting in variations in sludge composition and consistency between lagoons. An analysis of the sludge from the freshest, least viscous deposit (used in this S/S study) was conducted in 1987, with results for general characterization only. The sludge is primarily long-chain aliphatics, as expected with the residue from processing crude oil into lubricants. Constituents classified at that time as hazardous volatiles (boiling point <100°C) were not detected above the micrograms/liter (ppb) range. Sulfur, semi-volatile and nonvolatile hazardous constituents are present up to several hundred ppm.

The studied sludge has a consistency of a slow-curing asphalt, an ash content of 4.5 percent and a total organic carbon

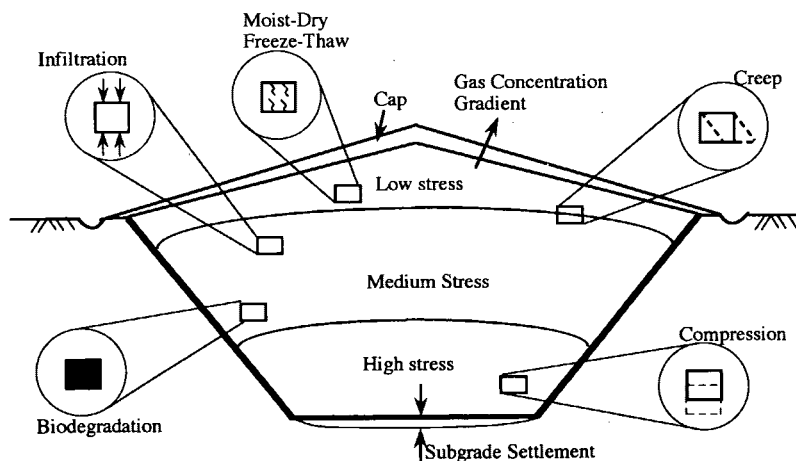


FIGURE 2 Internal and boundary stress environment of a landfill.

content of 35.3 percent. The sludge was divided into "solid" and "liquid" portions, based on the loss from a mixture oven-dried at 105°C for 24 hr.

Silty Clay

The onsite clayey silt is derived from weathering on the gneiss bedrock. X-ray diffraction tests indicate that kaolinite is the predominant clay mineral. The cation exchange capacity was measured at 49 meq/100gm and specific gravity was 2.72. Other indexes include a liquid limit of 31 percent and a plasticity index of 11, 86 percent fines and 8 percent clay-sized material. The soil is classified as ML by the Unified system. The Standard Proctor maximum dry unit weight is 17.3 kN/m³, with an optimum moisture content of 16 percent.

The natural soil exists in loamy peds or aggregations, but is readily pulverized. An array of structures can be formed, depending on compaction effort and moisture content. As the clayey silt is the skeleton of the S/S product, its hydraulic and mechanical properties indicate the expected values of the final solidified product. Undisturbed samples tested in a flex-wall permeameter at low confining stresses had a permeability of 4.5×10^{-5} cm/sec, and the natural structure displayed high compressibility. Compaction at 90 percent standard proctor unit weight, slightly wet of the optimum moisture content, reduced the permeability to 3×10^{-8} cm/sec. One-dimensional compression tests on the compacted samples showed a compression index (C_c) of 0.20 and a recompression index (C_r) of 0.04. Unconfined compression tests on compacted samples in the 15 to 20 percent moisture range showed thixotropy, with as-compacted strengths about 83 kN/m² (12 psi), increasing 50 percent over 30 days.

Additives

Lime neutralizes the sludge, appears to allow the emulsion to coalesce as globules, reduces clay plasticity, and is a component in the pozzolanic reaction. It also appears to condition the clay to immobilize the sludge. Reduced carbon solubility with lime was observed only in the presence of a fine-grained soil. Hydrated dolomitic lime was used to minimize heat and volatilization.

Bituminous coal fly ash was obtained from a nearby power plant, with a specific gravity of 2.54 and a median grain size (d_{50}) of 0.03mm. It met Type F criteria, except for excess carbon content, which was measured as 14.6 percent by the loss on ignition test. The fly ash serves as an absorbent to improve the blending of sludge and clay, and then participates in the pozzolanic cementing. It also appears to be a source of alkalinity during permeation with acidic solvents, thus improving the S/S longevity.

Lime-fly ash proportioning was varied over a range of water contents. Unconfined compressive strengths of 517 kN/m² (75 psi) and higher at moisture contents of 25 percent to 35 percent were obtained in 30 days. A lime-fly ash blend in the ratio of 1:3 was chosen for the stabilization. Addition of small amounts of cement to this blend substantially increased strength.

Mixtures

The properties of the sludge-clay-pozzolan mixtures depend on component proportioning, moisture content, age, sludge consistency, and compactive effort. The premise is that the soil structure is expanded and held at high porosity by a lime conditioning and inclusion of fly ash. With time, pozzolanic reactions improve strength. The resulting structure is conceptually illustrated on Figure 3, showing different pore channels between and within the cemented peds. The optimum mixture proportioning (by weight) for the high-viscosity sludge using a soil moisture content slightly below its optimum moisture content was found to be

1.0 sludge / 0.75 clayey silt / 0.75 fly ash / 0.25 lime

The fresh mixture had a "moisture" content of 11 percent after 24 hr of drying at 105°C, with losses including both water and organics. Compaction at 100 percent and 50 percent standard proctor effort yielded moist unit weights of 15.4 kN/m³ (98 lb/ft³) and 14.8 kN/m³ (91 lb/ft³), respectively. The volumetric proportioning, using constituent specific gravities, is computed as shown in Figure 4. This does not account for water produced by neutralization. It can be seen that the goal of a 50 percent sludge content was met, and there is a finite air content.

TYPICAL RESULTS

Samples for unconfined compression tests were compacted at 100 percent proctor effort in teflon molds, extruded, and cured in sealed containers. Lower compaction effort did not yield consistent results. A typical initial strength was about 69.0 kN/m² (10 psi), increasing to 110.3 kN/m² (16 psi) at 30 days, and 151.7 kN/m² (22 psi) at 60 days. Samples cured in molds showed 40 percent higher strength, indicating a confinement effect, which is expected to occur in the field.

One-dimensional compression results with the spent clay, at clay moisture contents bracketing the optimum moisture content and including a replication set are shown in Figure 5. Samples were obtained by pressing a cutter ring into a proctor mold of the prepared mixture. As expected, the wetter clay was softer, indicating that the mechanical skeleton is indeed the modified soil. Similar results and compression indexes were obtained with the main (Figure 4) native mixture.

Permeability results also showed effects of the fine-grained matrix structure. Samples were compacted at different levels of effort in fixed-wall, falling-head permeameters. Tests began after 14 days of curing. Permeability or hydraulic conductivity of 2×10^{-5} cm/sec was obtained with light compaction, decreasing to 3.5×10^{-7} cm/sec for samples compacted with 100 percent proctor effort. Results were insensitive to hydraulic gradient.

Permeation tests also yielded effluent samples. Both permeability and effluent quality were similar with dilute sulfuric acid, dilute acetic acid, and distilled water permeants (pHs of 2.5, 4, and 6, respectively). Thereafter, only distilled water was used, yielding effluent pH about 8.

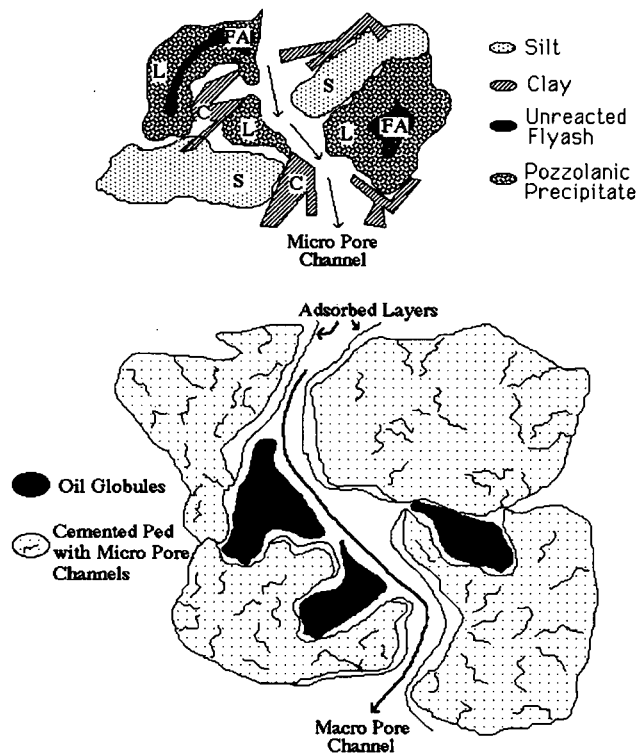


FIGURE 3 Conceptual model of stabilized product structure.

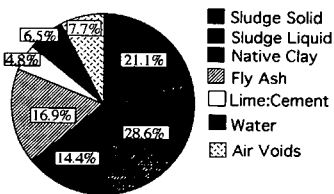


FIGURE 4 Volumetric proportions.

Illustrated in Figures 6 and 7 are the results of total organic carbon analysis on the effluent. Sample *EK* was a test with the spent clay, whereas curves 1A and 1B are results on the main mixture with the native clayey silt, but permeated at different gradients.

Although there was no phase separation in the effluent, it can be seen by Figure 6 that there is a "first flush" effect of

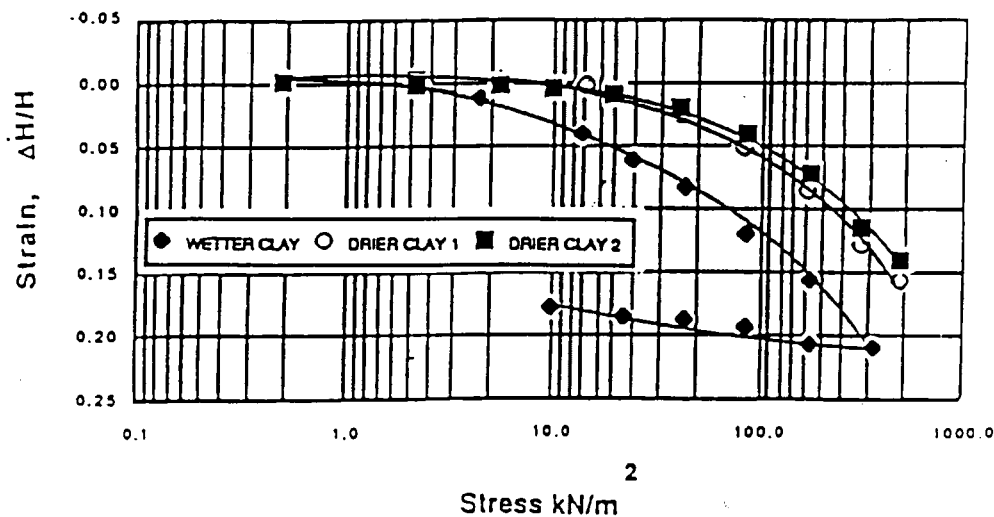


FIGURE 5 Compressibility sensitivity to soil moisture content.

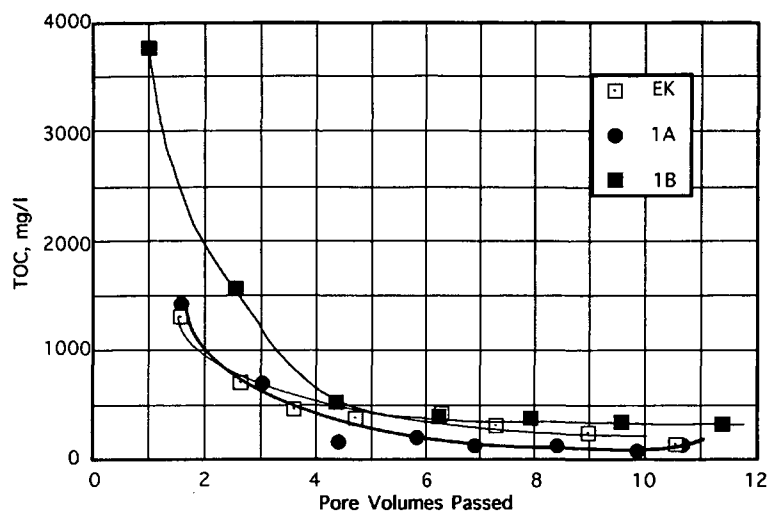


FIGURE 6 Permeameter effluent quality versus throughput.

very high carbon content. A better perspective on effectiveness is shown in Figure 7, indicating the accumulated percent of the sample carbon content mobilized. It can be seen that the less than 5 percent of the carbon was mobilized at throughputs that could represent many decades of infiltration. The difference between the No. 1A and No. 1B curves is a hydraulic detention time effect. The former was run at an average gradient of 60 cm/cm, and the latter at 10 cm/cm. The implication is that the rate-determining step in contaminant release is carbon transport from where it is entrapped or absorbed in the pore structure (see Figure 3) to the main interconnected channels.

STRENGTH IMPROVEMENT

The experimentation previously described was done with a composite sludge sample from the prototype lagoon. In tests with the more liquid sludge component, lower strengths and higher permeabilities were obtained. Drier clay improved initial strength, but the rate of strength gain was limited, perhaps because of a deficiency in moisture to complete the pozzolanic reactions. To increase strength, Type II portland cement was

substituted for the lime, keeping the proportioning of the other constituents constant. Results are illustrated in Figure 8, expressed in terms of relative lime and cement percentages (e.g., 100/0 represents no cement substitution, whereas 50/50 represents 50 percent replacement of the lime). It can be seen that the latter mixture had much higher strength.

A pilot set of permeation and consolidation tests on the higher cement content mixture indicated more carbon mobilization with higher cement replacement of the lime and no variation in the stiffness. This confirms that the clayey silt skeleton dominates compressibility and that lime-clay interaction dominates the immobilization. Consequently, the 85/15 lime/cement ratio was selected, giving a net proportioning (by weight) of

1.0 Sludge / 0.75 Clayey Silt / 0.75 Fly Ash /
0.21 Lime / 0.04 Cement

CONCLUSIONS

This laboratory project demonstrated the feasibility of solidifying a hydrocarbon sludge in a very porous, cemented fine-grained soil matrix. The mixtures usually do not meet the

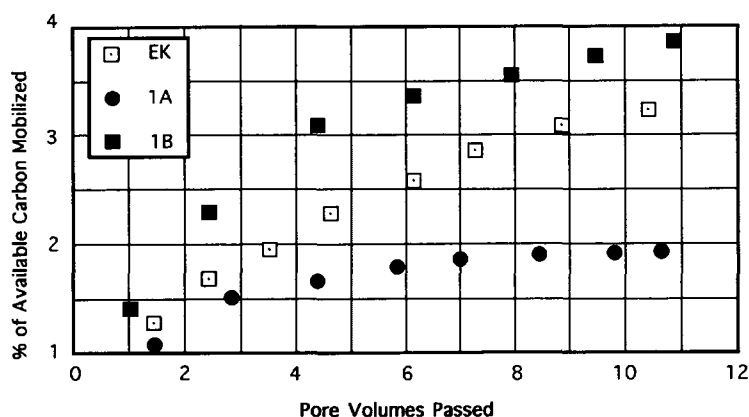


FIGURE 7 Accumulated quality of permeation effluent.

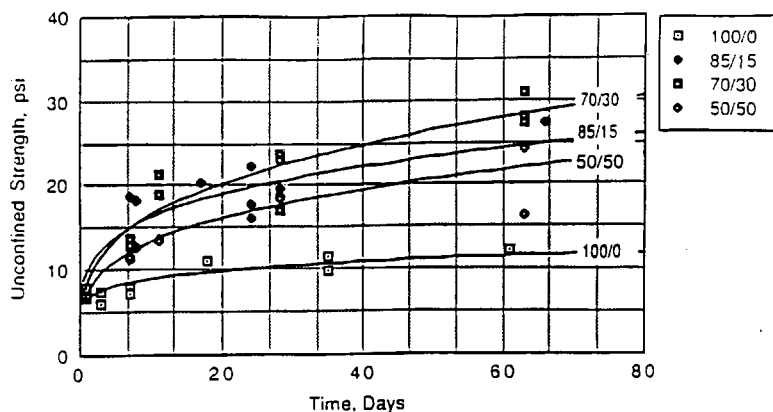


FIGURE 8 Effect of cement addition on strength gain.

mechanical values often specified for hazardous materials, but engineering analysis shows that the results are adequate for dimensionally stable and impervious capped landfill monoliths. The underlying point is that field performance depends on the in situ conditions as well as material properties. Compressibility and unconfined compressive strengths were acceptable when the overburden stress is accounted for and the deformation criteria are expressed as slope stability, zero liquid expulsion, and uniform cap support.

In this investigation, a soil-like texture was readily obtained. Depending on the factors that would be expected to be influential (clay moisture content, compactive effort, sludge consistency, additive proportioning, etc.), hardened material properties vary up to an order of magnitude. Permeability was the most sensitive property, as would be expected for a fine-grained soil. Compressibility was the least sensitive, possibly because of the pozzolanic cement compensating for factors that soften the soil skeleton. The shear strength was most sensitive to sludge consistency, but this could be compensated for by the addition of portland cement.

Exactly what happens to the microencapsulated hydrocarbons distributed through the porous matrix is not well understood, but the contrast between immobilization with and without a fine-grained soil matrix was dramatic. Hydrocarbon mobility was radically decreased. Similar results were obtained with two fine-grained soils of different index properties. The slow internal transport to advective channels during permeation implies a potential for immobilization mechanisms such as sorption on particle surfaces or an organic layer, and possibly embedment in pozzolanic precipitates. The extent to which the stabilization component of S/S can be considered a success depends on regulatory requirements.

S/S of a viscous hydrocarbon sludge with cemented silty clay implies feasibility for onsite improvement of subgrades contaminated with similar highly viscous organic materials.

ACKNOWLEDGMENT

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REFERENCES

1. Winterkorn, H. T. *Soil Stabilization*, Foundation Engineering Handbook (H. F. Winterkorn and H. Y. Fang, eds.), Van Nostrand Reinhold, New York, 1975.
2. Handbook for Stabilization and Solidification of Hazardous Wastes. Environmental Protection Agency, EPA/540/2-86/001, 1986.
3. Smith, C. L., and D. J. Frost. Secure Landfilling with Pozzolanic Cementing, In Proc., 1st Annual Conference on Hazardous Waste Management, Philadelphia, Pa., pp. 153-160, 1983.
4. Morgan, D. S., J. I. Novoa, and A. H. Half. Oil Sludge Solidification using Cement Kiln Dust, *Journal of Environmental Engineering*, Div., ASCE 110 (EE5), 1984, pp. 935-949.
5. Cullinane, M. J. *An Assessment of Materials that Interfere with Solidification/Stabilization*. Environmental Protection Agency, EPA IAG SW-219306080-01-0, 1988.
6. Webster, W. C. Role of Fixation Practices in the Disposal of Wastes. *ASTM Standardization News*, 1984.
7. Poon, C. S. A Review of Evaluation Procedures for Stabilization/Solidification Processes: Environmental Aspects of Stabilization and Solidification of Hazardous and Radioactive Wastes. ASTM STP 1033, 1989, pp. 114-124.
8. Martin, J. P., A. J. Felser, and E. L. Van Keuren. Hydrocarbon Waste Stabilization for Landfills. *ASCE Specialty Conference for Waste Disposal*, Ann Arbor, Mich., 1987.
9. Martin, J. P., J. S. Browning III, K. Adams, and W. T. Robinson. Modeling Mobilization from Stabilized Refinery Waste Deposits by Sequential Leaching, Petroleum Hydrocarbons and Organic Chemicals in Ground Water, NWWA-API, Houston, Tex., Nov. 1989.
10. Martin, J. P., F. J. Biehl, J. S. Browning III, and E. L. Van Keuren. Constitutive Behavior of Clay and Pozzolan Stabilized Hydrocarbon Refining Waste. In Proc., *Geotechnics of Waste Fills*, ASTM STP 1070, San Francisco, Calif., June 1990.
11. Browning III, J. S., and F. J. Biehl. Evaluation and Analysis for Subsidence of Stabilized Sludge. *Proc. 22nd Mid-Atlantic Industrial Waste Conference*, Philadelphia, Pa., July 1990, pp. 594-609.
12. Robinson, W. T. *Characterizing the Leaching Potential of Hydrocarbon Wastes from a Stabilized Mixture*. M.S. thesis, Drexel University, Philadelphia, Pa., 1987.
13. Browning III, J. S. *Stabilization and Solidification of a Hydrocarbon Refining Sludge: Engineering Optimization and Performance Analysis*. M.S. thesis, Drexel University, Philadelphia, Pa., 1990.

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Environmental and Engineering Properties of Flue Gas Desulfurization Gypsum

RAMZI TAHA

As a result of sulfur oxides (SO_x) emissions control for power plants burning lignite or sulfur coals, 18,000,000 Mg (20 million tons) of flue gas desulfurization (FGD) gypsum are generated annually in the United States. One application under which the material is being considered for use is in road base-subbase construction. Presented in this paper is a summary of the physical and chemical characterization, the radiological and leachate analysis, and the mechanical properties of FGD gypsum. Preliminary laboratory data indicate that cement stabilized FGD gypsum mixtures should perform satisfactorily in road base-subbase construction. However, further laboratory and field data are needed to fully understand and evaluate the properties of these materials.

Ever-increasing highway construction costs coupled with a geographic shortage of good-quality materials continually spur interest in the search for alternate construction methods and materials. In many locations, such as in the Gulf Coast area, aggregates must be hauled several hundred miles, thereby adding significant transportation charges to the cost of the construction. One material currently existing in large quantities in Florida, Louisiana, and Texas that could help relieve this problem is by-product gypsum. By-product gypsums are usually given designations to reflect the specific chemical process that produced them (e.g., phosphogypsum, flourogypsum, FGD gypsum, and so on).

FGD gypsum, a by-product of sulfur oxides recovery operations at power plants burning coals, is one such system. Sulfur, a natural contaminant of coal, is almost completely converted to sulfur oxide when coal is burned. FGD processes result in SO_x removal by inducing exhaust gases to react with a chemical absorbent as they move through a scrubber (1). The absorbent (limestone, calcium hydroxide, or calcium oxide) is dissolved or suspended in water forming a solution or slurry that can be sprayed or otherwise forced into contact with the escaping gases.

Pumped in a slurry form to stockpiles, this material consists predominantly of either calcium sulfite (CaSO_3) or calcium sulfate (CaSO_4) crystals. The crystals can further exist in at least three forms: anhydrite, hemihydrate, or dihydrate. This material has a grain size distribution similar to silt and is very friable in nature.

According to Dean Golden (unpublished data), 18,000,000 Mg (20 million tons) of FGD gypsum are generated annually in the United States. With the enactment of the recent Clean

Air Act legislation, the current plants will probably add another 18,000,000 Mg (20 million tons)/year of FGD gypsum. The total current inventory of the material is approximately 136,000,000 Mg (150 million tons). In 40 years, it is estimated that the amount of FGD gypsum will quadruple.

During the past 7 years, Texas A&M University has been involved in an ongoing research effort involving the development of cost-effective use of FGD gypsum with the objective of evaluating its potential for use in road bases and subbases (2-4).

Two experimental roads were completed in 1988 and 1989 (2,3). Cement and cement-fly ash stabilized FGD gypsum test sections were used as base materials. However, some road sections did not perform satisfactorily and had to be replaced. Contributing factors for this poor performance of the material include stabilizers selection, construction practices, and subgrade conditions.

OBJECTIVE

The main objective of this paper is to summarize the results of physical, chemical, radiological, leachate, and mechanical tests performed on FGD gypsum. Particular attention is given to the use of FGD gypsum as a subbase-base material in road construction.

MATERIALS

FGD Gypsum

The FGD gypsum used in the research study is produced by the Texas Utilities Generating Company (TUGCO) at their Martin Lake Power Plant in Tatum, Texas. The material consists mainly of calcium sulfate crystals and is currently being produced at 18 other plants in Texas at a total rate of 900,000 Mg (1 million tons)/year. FGD gypsum was collected in 45, 18.9-L (5-gal) capacity buckets over a period of 90 days for the characterization studies.

Portland Cement

The portland cement used in the research program was a commercial Type II cement meeting the requirements of ASTM

C150. The cement was a sulfate-resistant cement with a tricalcium aluminate (C_3A) content of 3.06 percent. The bulk cement was purchased from Texas Industries of Midlothian, Texas.

EXPERIMENTAL RESULTS

The research program encompassed physical and chemical characterization, radiological and leachate analysis, moisture-density relations, unconfined compressive strength testing, and dynamic modulus and flexural fatigue tests. The following sections summarize the results of these studies and include recommendations for further study.

Physical Properties

The physical properties of FGD gypsum are as follows:

Property	Average ^a
Free moisture	14%
Structural moisture	26%
Specific gravity	2.30
< #325 sieve	53%

^aAverage of 90 samples.

A free moisture of 14 percent was obtained by drying the material at 40°C (104°F). At temperatures above 70°C (158°F), all chemically or structurally bonded water (about 26 percent) will also be removed (5). FGD gypsum exhibits little or no plasticity. Based on the Unified Soil Classification System (USCS), the material would be classified as ML (a silt with little or no plasticity). One hundred percent of the material fraction will pass the No. 4 sieve and more than 60 percent will pass the No. 200 sieve. The absence of plasticity in gypsum and its silt-sized grain-size distribution have been confirmed by Blight (6) and Knight et al. (7).

Chemical Properties

The chemical breakdown of FGD gypsum is as follows:

Constituent	Content (%)
Ca	24
SO ₄	54
CO ₃	3
SiO ₂	2.7
Inert	1.3

The material consists mainly of calcium (Ca) and sulfate (SO₄) crystals. The pH of FGD gypsum is approximately 6.6. Also, a number of trace elements are present in the material. Typical leachate concentrations of these elements are listed in Table 1. The concentrations of the leachable metals from fresh FGD gypsum are well below the EPA Leachate Standards. The leachate analysis on the samples was conducted in 1988 in accordance with the Extraction Procedure (EP) toxicity characteristic test. However, in March of 1990, the Environmental Protection Agency (EPA) replaced the EP toxicity test by the Toxicity Characteristic Leaching Procedure (TCLP). No TCLP test data are available on fresh or stabilized FGD gypsum.

Environmental Characterization

The environmental testing program consisted of radiological and leachate testing.

Radiological Testing

A radiological evaluation was conducted by Erdman and Vasquez (8) on 12 samples of FGD gypsum. The testing included an analysis of the existing gross beta and alpha activities as well as the Radium-226 content. The results of this analysis are given in Table 2. No significant radiological differences were found between any of the 12 samples. The Radium-226 concentrations were in the same range as literature values (0.1 to 0.3 pCi/g) for typical soils (9) and (0.3 to 5.3 pCi/g) for cement (10). Erdman and Vasquez conclude in the report (8) that "all of the FGD gypsum samples are radiologically similar and pose no greater risk than typical construction materials in use today."

Leachate Testing

The leachate analysis of the trace elements present in a mixture of FGD gypsum stabilized with 11 percent Type II portland cement was conducted using the EP Toxicity test. The results, which are listed in Table 3, indicate that the leachate quality is well within the EPA Leachate Standards. It is well

TABLE 1 Results of the Leachate Analysis of Fresh FGD Gypsum

Element	EP Toxicity ^a (mg/L)	EPA Leachate Standards (mg/L)
As	<0.01	5.0
Ba	<0.50	100.0
Cd	<0.005	1.0
Cr	<0.05	5.0
Pb	<0.05	5.0
Hg	<0.005	0.2
Se	<0.01	1.0
Ag	<0.05	5.0

^aMethod 40CFR261.

TABLE 2 Radiological Evaluation of FGD Gypsum

Sample Number	Gross Alpha (pCi/g)	Gross Beta (pCi/g)	Ra-226 (pCi/g)
1	7.1	1.5	0.44
2	7.1	1.5	1.20
3	7.1	1.5	1.90
4	7.1	1.5	1.20
5	6.4	1.2	0.44
6	6.4	1.2	1.20
7	6.4	1.2	0.44
8	6.4	1.2	0.44
9	6.4	1.2	0.44
10	6.4	1.2	1.0
11	6.4	1.2	1.2
12	6.4	1.2	1.1

TABLE 3 Results of the Leachate Analysis of a Mixture of FGD Gypsum Stabilized with 11% Type II Portland Cement

Element	EP Toxicity ^a (mg/L)	EPA Leachate Standards (mg/L)
As	<0.01	5.0
Ba	<0.50	100.0
Cd	<0.005	1.0
Cr	0.19	5.0
Pb	0.17	5.0
Hg	<0.005	0.2
Se	<0.01	1.0
Ag	<0.05	5.0
pH	11.9	2.0–12.5

^aMethod 40CFR261.

to keep in mind that because of the soluble nature of unstabilized FGD gypsum, a high concentration of sulfate may be found in the leachate. There is no leachate standard for sulfate at the present time. However, there is an EPA drinking water standard for SO_4 and it was recently reduced from 300 mg/L to 200 mg/L.

Mechanical Properties

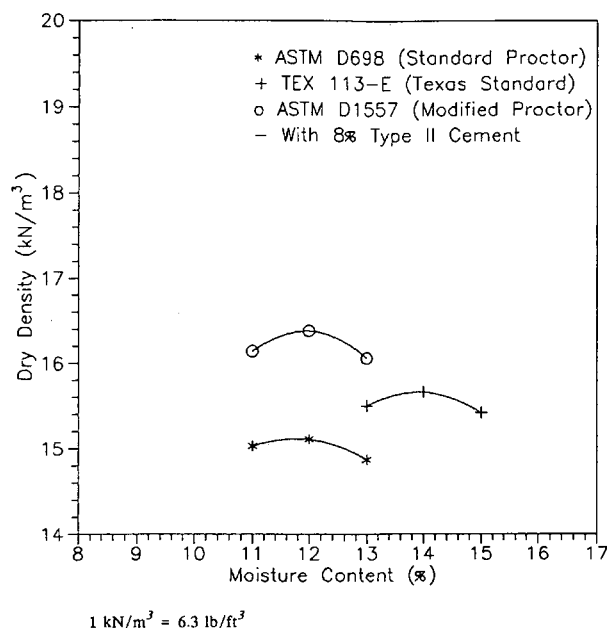
Mechanical tests performed on stabilized FGD gypsum mixtures include moisture-density relations, unconfined compressive strength, dynamic modulus, and flexural fatigue. Discussed in the following sections of the paper will be the results of each individual test. Freeze-thaw, permeability, and triaxial data obtained on stabilized FGD gypsum mixtures can be found in other references (3,4).

Moisture-Density Relationships

Strength development in FGD mixtures can be achieved through stabilization with either Portland cement, fly ash, or combinations thereof. The optimum moisture content and maximum dry density values will be influenced by the method of compaction, the curing time, and the type and amount of stabilizers used (if any). Shown in Figure 1 are the moisture-density relationships for gypsum mixtures stabilized with 8 percent Type II cement and compacted in accordance with ASTM D1557—Method A (modified Proctor), ASTM D698 (standard Proctor) and Texas Method 113E. The Texas method specifies a compaction energy of 0.001 m-N/mm³ (12.3 ft-lb/in³) and falls in between the two Proctor methods. The modified and standard Proctor compaction procedures yielded an optimum moisture content of 12 percent as compared with 14 percent moisture obtained using the Texas method. Higher maximum dry density values were obtained with the higher compaction energy levels.

Unconfined Compressive Strength Testing

After completing the compaction series, duplicate specimens were prepared at optimum moisture content for strength determination using the unconfined compression test (ASTM

**FIGURE 1 Moisture-dry density relations of cement stabilized FGD gypsum mixtures prepared under different compaction procedures.**

D1633). This method prescribes either a 101.6-mm (4-in.) diameter by 116.43-mm (4.584-in.) specimen—Method A ($L/D = 1.15$), or a 71.12-mm (2.8-in.) diameter by 142.24-mm (5.6-in.) specimen—Method B ($L/D = 2$). The former method was used because it was consistent with the modified Proctor compaction methodology. Molded specimens were cured in plastic bags before compression testing. The 7-day compressive strength results for cement stabilized gypsum mixtures prepared and compacted in accordance with the three compaction procedures previously described are shown in Figure 2. With an increase in cement content and compactive effort, there is an increase in the unconfined compressive strength.

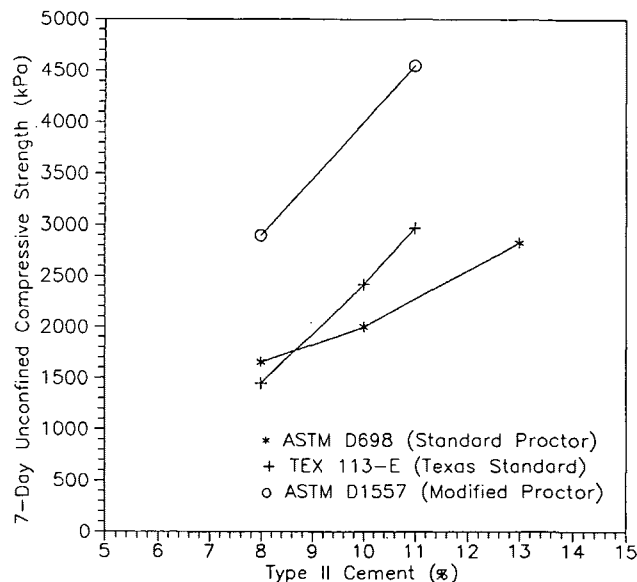
Resilient Modulus Testing

The resilient modulus (M_R) is a dynamic test response defined as the ratio of the repeated axial deviator stress (σ_d) to the recoverable axial strain (ϵ_a). Test conditions (e.g., stress state, moisture content, compactive effort) affect M_R responses for different materials in different ways. The test is conducted in a triaxial device equipped for repetitive load conditions.

Resilient modulus testing was conducted on mixtures of FGD gypsum stabilized with 6 and 8 percent Type II cement. The specimens used were 101.6 mm (4 in.) in diameter by 203.2 mm (8 in.) high and were prepared so as to meet the compaction level set forth in ASTM D1557—Method A. The specimens were then wrapped in plastic bags and cured for 16 days at 23.3°C (74°F) and 100 percent relative humidity. Deformations were measured by using linear differential transformers (LVDTs) clamps bonded directly to the specimens. To minimize any extraneous deformation that may oc-

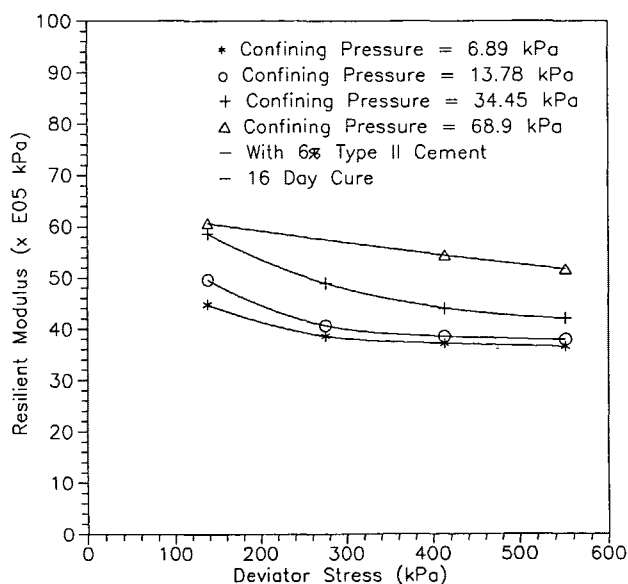
cur within the load piston and end plates during the test, the LVDT clamps were placed near the quarter points of the specimen.

Typical results obtained from the resilient modulus testing on cement stabilized FGD gypsum mixtures are shown in Figures 3 and 4. The reason for using the high deviator stresses in those experiments is the difficulty encountered in getting



1 kPa = 0.145 psi

FIGURE 2 Seven-day unconfined compressive strength for cement-stabilized FGD gypsum mixtures prepared under different compaction procedures.



1 kPa = 0.145 psi

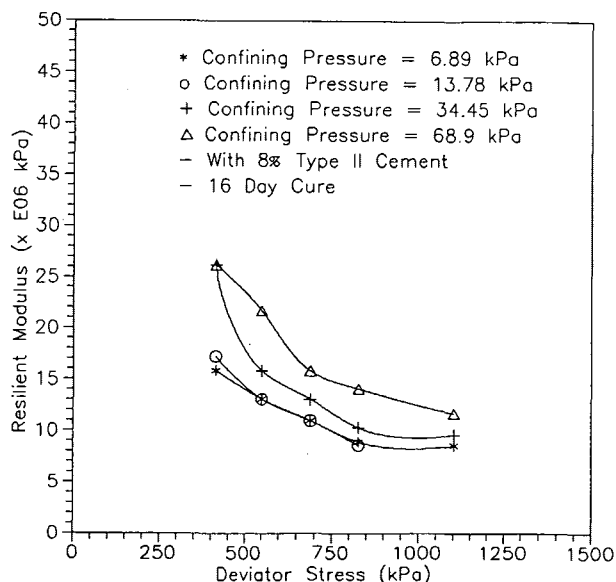
FIGURE 3 Resilient modulus of FGD gypsum stabilized with 6 percent Type II cement.

any readings at the low stress levels. The resilient modulus for FGD gypsum stabilized with 6 percent Type II cement and tested at a bulk stress of 590 kPa (86 psi) is about 3,800,000 kPa (550,000 psi), whereas that mixture stabilized with 8 percent Type II cement and tested at the same bulk stress yielded a resilient modulus value of 12,000,000 kPa (1,750,000 psi). Such results are compared against different base materials in Figure 5. On the basis of the resilient modulus data, stabilized FGD gypsum blends should perform as well as any other conventional base materials in road base applications. However, the tensile strength data of cement stabilized FGD gypsum mixtures should be obtained and correlated with the resilient modulus data. If the resilient modulus of a stabilized material increases without a corresponding increase in tensile strength, it is likely to undergo tensile cracks.

Flexural Fatigue Testing

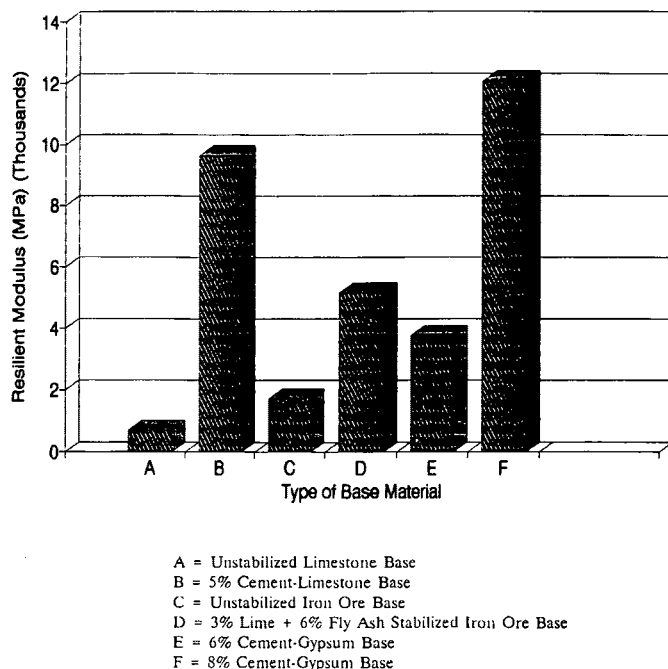
Research has demonstrated how shear strength in the pavement, flexural strength, and flexural fatigue life can be used to provide reliable acceptance criteria for the design of stabilized bases. In this study, flexural fatigue tests were used to develop a relationship between the unconfined compressive strength, the fatigue strength, and the resistance to low-temperature cracking.

Test specimens were prepared by compacting cement/FGD gypsum blends into 76.2 x 76.2 x 387.4-mm (3 x 3 x 15 1/4-in.) steel molds in two equal layers (6, 8, and 10 percent Type II cement were used in the preparation of the mixtures). The surface of the first layer was scarified before placement of the second layer to ensure bonding. Compaction was accomplished through a hammer with a 50.8-mm (2-in.) diameter base. The compactive effort was applied by a 44.5-N (10-lb)



1 kPa = 0.145 psi

FIGURE 4 Resilient modulus of FGD gypsum stabilized with 8 percent Type II cement.



1 MPa = 145 psi

FIGURE 5 Comparison of resilient moduli values of cement-stabilized FGD gypsum mixtures with conventional base materials.

weight free falling 457.2 mm (18 in.). Each layer received 75 blows to simulate the energy employed by ASTM D1557—Method A. The average dry density in the specimens was about 15.2 kN/m³ (97 lb/ft³). The specimens were then wrapped in plastic bags and placed in a curing room at 23.3°C (74°F) and 100 percent relative humidity. The samples were cured for 30 days. The length of cure was assumed to be representative of field conditions. After removal from the curing room, the specimens were tested at ambient room temperature and no attempt was made to control the temperature during the fatigue test.

The stress level in a fatigue test is commonly defined as the ratio of the applied stress to the static ultimate strength of the material. The flexural test specimens were tested under three-point loading and all samples were loaded at a constant rate of 1.27 mm/min (0.05 in/min) for measuring the static strength of the cement/FGD gypsum blends. Stress in the specimen was calculated assuming a constant cross-sectional area and a linear stress distribution. The loads in the dynamic test were applied at a rate of 720 cycles/min and the number of cycles to failure for each applied load was then recorded.

The results from the fatigue tests on the three mixtures are shown in Figures 6 and 7. It can be seen in Figure 6 that when the fatigue data are plotted as applied stress (σ_{applied}) versus the number of cycles to failure (N_f), a curve exists for each mix design. However, when the results are plotted as the ratio $\sigma_{\text{applied}} / \sigma_{\text{flexure}}$ as in Figure 7, all data can be presented by one curve. This ratio equals 0.60 at $N_f = 10^5$ cycles. Furthermore, it was shown from the static fatigue data that the

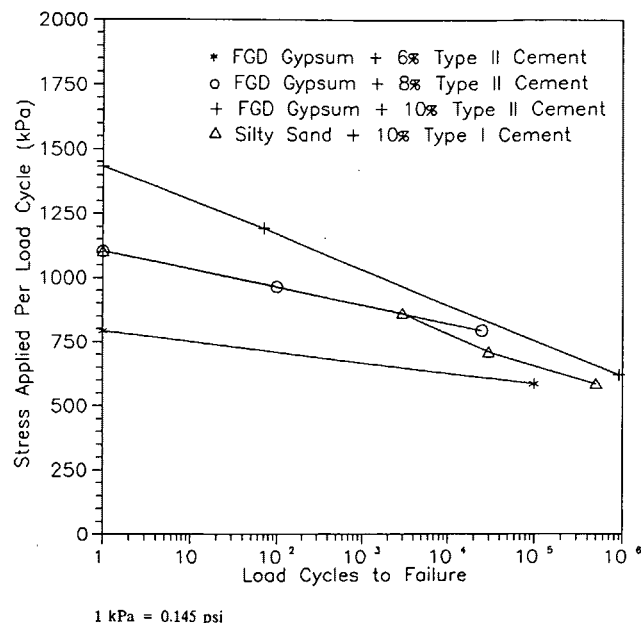


FIGURE 6 Stress applied versus number of load cycles to failure for various cement-stabilized mixtures.

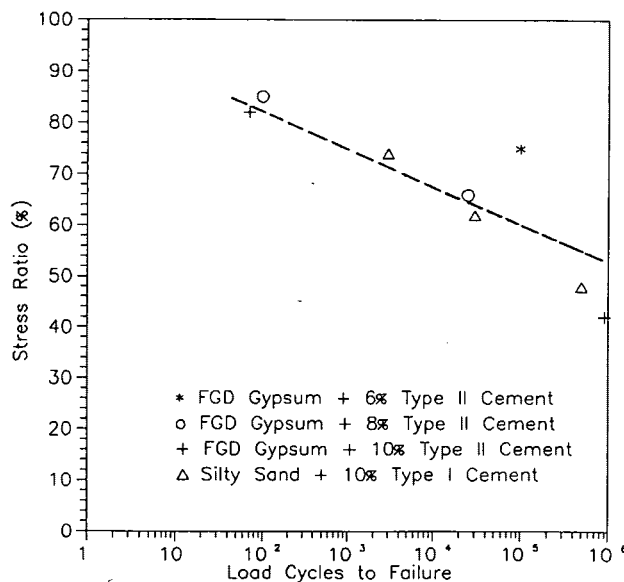


FIGURE 7 Stress ratio versus number of load cycles to failure for various cement-stabilized mixtures.

flexural strength is approximately 0.2 times the unconfined compressive strength (UCS),

$$\sigma_{\text{flexure}} = (0.2) (\text{UCS})$$

But

$$0.6 = \sigma_{\text{applied}} / \sigma_{\text{flexure}} \text{ at } N_f = 10^5 \text{ cycles}$$

Therefore

$$0.6 = \sigma_{\text{applied}} / (0.2) \text{ (UCS)}$$

or

$$\text{UCS} = (8.5) (\sigma_{\text{applied}})$$

This indicates that the compressive strength is of the order of 8.5 times the applied stress to cause failure in the road base. In a well-designed pavement system, this applied stress can be between 205 and 275 kPa (30 and 40 psi). On this basis, the design strength should be around 2050 kPa (300 psi) instead of the 4500 kPa (650 psi) strength that is normally required for base materials subjected to freeze-thaw cycles (Texas State Department of Highways and Public Transportation specifications). A demonstrated test fatigue life in excess of 10^5 cycles would be satisfactory for roads with low traffic volume, whereas 10^8 cycles would suffice for high traffic volumes. The latter would also demonstrate good resistance to low temperature as well as freeze-thaw cracking.

CONCLUSIONS

The results from the laboratory studies conducted on FGD gypsum warrant the following conclusions:

1. The radiological analysis indicates that FGD gypsum poses no risk if used as a road subbase-base material or in any other applications.
2. The results of the EP toxicity leachate tests indicate that fresh or stabilized FGD gypsum will meet the EPA Leachate Standards.
3. Compactive effort has a significant influence on the dry density and compressive strength of stabilized FGD gypsum mixtures.
4. Preliminary resilient modulus and flexural fatigue testing data indicate that stabilized FGD gypsum mixtures should perform satisfactorily as road base and subbase materials.

RECOMMENDATIONS

Further laboratory testing is needed to evaluate the properties of stabilized and unstabilized FGD gypsum mixtures. Wet-

dry, expansion, tensile strength, and water submersion data should be obtained on these mixtures. Furthermore, the leachate analysis should be conducted using the Toxicity Characteristic Leaching Procedure.

ACKNOWLEDGMENT

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REFERENCES

1. Controlling Sulfur Oxides. A Summary Report, EPA-600/8-80-029, Environmental Protection Agency, Research Triangle Park, N.C., 1980.
2. Taha, R., R. K. Seals and D. Saylak. Pre- and Post-Construction Evaluations of a Road Constructed With Stabilized FGD Gypsum Mixtures. In *Proc., 84th Annual Meeting and Exhibition of the Air and Waste Management Association, Vancouver, B.C., Canada*, June 1991.
3. Taha, R. Utilization of By-Product Gypsum in Road Construction. Ph. D. dissertation, Texas A&M University, College Station, Dec. 1989.
4. Saylak, D., M. P. J. Olsen and R. Taha. Investigation of Martin Lake Synthetic Gypsum. Report by the Civil Engineering Department to the Texas Utilities Generating Company (TUGCO), Texas A&M University, College Station, Jan. 1986.
5. Wirsching, F. Drying and Agglomeration of Flue Gas Gypsum. In *Proc., 1983 ASTM Symposium on Gypsum and Related Building Materials and Systems*, STP 861, Philadelphia, Pa., 1983.
6. Blight, G. E. Waste Gypsum as an Embankment Material. In *Proc., 7th International Conference on Soil Mechanics and Foundations Engineering*, Mexico, 1969.
7. Knight, R. G., E. H. Rothfuss and K. D. Yard. FGD Sludge Disposal Manual. CS-1515-Research Project 1685-1, Electric Power Research Institute, Palo Alto, Calif., 1980.
8. Erdman, C. A., and G. M. Vasquez. A Radiological Evaluation of TUGCO Natural and Synthetic Gypsum. Report by the Nuclear Engineering Department to the Texas Utilities Generating Company (TUGCO), Texas A&M University, College Station, May 1984.
9. Kathren, R. L. Radioactivity in the Environment. Harwood Academic, New York, N.Y., 1984.
10. Schmier and Kolb. Natural Radioactive Substances in Building Materials, 1977.

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Unconfined Compressive Strength of Various Cement-Stabilized Phosphogypsum Mixes

S. ONG, J. B. METCALF, R. K. SEALS, AND R. TAHA

The unconfined compressive strength of various cement-stabilized phosphogypsum mixes is described. The mixes vary in compacted dry unit weight, moisture content, cement type and content, and curing procedure and time. It is shown that the mixes behave in similarly to cement-stabilized soil. The strength increases with increases in dry unit weight, cement content, and curing period. Strength decreases with increasing compaction moisture content and with a soaked curing regime. The strengths exceed a typical minimum specified unconfined compressive strength (1.7 MPa at 7 days) only at modified Proctor compacted densities (at 4 percent cement) and more than 14 percent at standard Proctor compaction level. A limited study of the effects of adding sand, hydrated lime, and calcium chloride showed that sand and small additions of calcium chloride increase the 7-day strength. Lime was ineffective. The use of constant volume molds was also shown to be effective in allowing direct control of unit weight and moisture content in compacted specimens.

Phosphogypsum is a non-hazardous by-product of the manufacture of phosphate fertilizers. It is being produced at the rate of 36 million Mg in the United States, where stockpiles are estimated to reach 1.8 billion Mg by 2000. A search for uses of this industrial by-product has been under way for some time (1), and there is potential for use in agriculture, as a soil conditioner; in building, for the production of plaster sheet; and in chemical engineering, as a source of sulfuric acid and other chemicals. All these uses are constrained to some degree by the presence of impurities, by a concern for potential environmental hazards and by the economics of the use of phosphogypsum in competition with alternative materials. A potential major use exists in civil engineering, where the material can be used as fill for road base and for cast block applications, such as artificial reef construction. The potentially large-volume uses of this nature are particularly attractive.

However, the road base and cast block applications require enhanced properties of the material, and stabilization of some form is necessary to achieve adequate properties for such uses. The stabilization process must be inexpensive and simple to be acceptable and to compete with other materials and processes.

The research described herein addresses the properties of cement-stabilized phosphogypsum (CSPG), principally unconfined compressive strength, and discusses the interaction of compacted density and moisture content, cement type and

content, curing regimes, and the effects of the admixture of sand, hydrated lime and calcium chloride as secondary additives.

PREVIOUS WORK

Stabilization of phosphogypsum for road base construction is not new (2), and several earlier studies have been carried out, for example, in Florida (3), Louisiana (4), and Texas (5). Generally these studies showed that phosphogypsum, which is poorly crystallized calcium sulphate dihydrate, with small quantities of impurities, behaves like silty soil. Tables 1 and 2 give typical properties of Louisiana phosphogypsum (4). In the natural state the phosphogypsum is not suitable for road base. The addition of cement typically results in a change in the compacted unit weight and optimum moisture content and an increase in unconfined compressive strength. Phosphogypsum stabilized with cement is suitable for use as road base; both full-scale experiments and actual construction projects have demonstrated this in Texas (6) and Florida (7,8).

The properties of the CSPG depend on the source and nature of the phosphogypsum, of the cement type and content, and of the construction process. Because of the intrinsic variability of all three, any particular application requires a study of the specific mixtures to be used. An area of concern currently receiving increased attention is the low level of radioactivities exhibited by phosphogypsum originating from Florida phosphate rocks (9). Studies of the effects of stabilization on radon emanation will be part of future research at the Institute for Recyclable Materials, Louisiana State University. Radon emanation is a key issue in Environmental Protection Agency regulation currently under review.

PROPERTIES OF CSPG

This paper describes current studies at the Institute for Recyclable Materials that are directed to the design and conduct of full-scale field experiments with CSPG pavements. It is planned to prove the suitability of the product and to develop appropriate material and construction specifications for road base in Louisiana, where the lack of natural aggregate deposits has resulted in soil stabilization being widely used for road base. Because some 91 million Mg of phosphogypsum is stockpiled in the state, the potential for CSPG road base construction warrants serious and early consideration.

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TABLE 1 Results of Chemical Analysis of Louisiana Phosphogypsum

Constituent	Content (%)
CaO	29 - 31
SO ₄	50 - 53
SiO ₂	5 - 10
F	0.3 - 1.0
P ₂ O ₅	0.7 - 1.3
Fe ₂ O ₃	0.1 - 0.2
Al ₂ O ₃	0.1 - 0.3
pH ^a	2.8 - 5.0

^a pH: not measured as a percent.

The study initially examined the effect of moisture, dry unit weight, cement type and content, and curing procedure and time on the unconfined compressive strength of the CSPG. Unconfined compressive strength is the common criterion for the suitability of stabilized soils for road base with a 7-day strength of 1.7 MPa frequently adopted as a minimum (10).

A second exploratory series of tests examined the effect of secondary additives on the unconfined compressive strength.

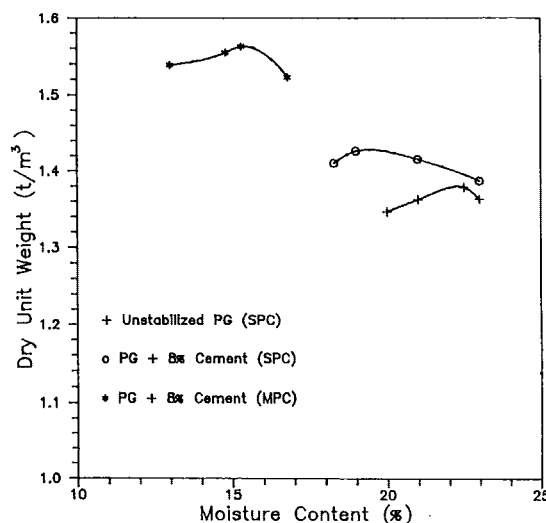
Moisture-Unit Weight Relations

The strength and bearing capacity of earthen materials depend critically on the compacted dry unit weight and moisture content. However, the addition of cement to soil usually changes the compacted dry unit weight and optimum moisture content for both standard and modified Proctor compaction; the first task was to establish these parameters for samples of phosphogypsum produced in Louisiana. Figure 1 shows a typical result, and Table 3 summarizes the tests conducted as part of this study.

The results are typical of the behavior of a cement-stabilized material and show standard Proctor compaction (ASTM D698) maximum dry densities of the order of 1.4 T/m³ at moisture contents of the order of 20 percent. The modified Proctor (ASTM D1557) maximum dry densities were 10 to 15 percent higher at 15 to 30 percent lower moisture contents. (Note that this moisture content is derived by drying at 55°C; a higher drying temperature than 60°C will decompose the phosphogypsum into a hemihydrate form.)

TABLE 2 Results of Physical Analysis of Louisiana Phosphogypsum

Property	Value
Free Moisture (Top)	8 - 18% (Varies with depth)
Free Moisture (phreatic water)	25 - 30%
Specific Gravity (Average)	2.35
Fineness (< # 200 sieve) (Average)	75%

**FIGURE 1 Effect of cement content on compacted dry unit weight and optimum moisture content.**

Cement Type and Content

The effect of cement type and content on unconfined compressive strength (ASTM D1633) was investigated by preparing samples by both standard and modified compaction. Typical results are shown in Figures 2 and 3. The results again showed typical behavior, with unconfined compressive strength increasing with cement content but varying with cement type. Type I (ordinary portland cement), Type II (moderate sulphate resistance), Type IIA (a low C3A cement), and Type V (high sulphate resistance) cements were used initially. The Type IIA cement was included as earlier studies by Freeport-McMoRan and others (11) had shown that a high C3A content could lead to expansion of the CSPG. The formation of ettringite is a possible cause (12), and studies of the fundamental mechanisms are continuing. However, the ASTM D1633 procedure, representing the constant compactive effort process used in construction, does not separate the effects of cement content from those of dry unit weight and moisture content changes the standard and modified Proctor dry densities at only the moisture content actual. Later tests, described in the following, were addressed to this issue and also examined the effect of a Type III (high early strength) cement.

Curing

Most samples were cured in double-sealed plastic bags at a constant temperature (70°F) for 7, 28, 56, 90, and 180 days. Selected mixes were also cured for 7 days by this procedure and then soaked for 21 days in water at room temperature. The soaked curing regimes generally reduce strength gain and may reduce the strength below that achieved at 7 days (Figure 4).

ADEQUACY FOR ROAD BASE

The results of the first series of tests demonstrated that CSPG behaved as a typical cement-stabilized road base material.

TABLE 3 Range of Dry Unit Weight and Moisture Content

Cement Type/Content ^a (%)	Compaction Procedure			
	Standard Proctor		Modified Proctor	
	Dry Unit Weight (t/m ³)	Moisture Content (%)	Dry Unit Weight (t/m ³)	Moisture Content (%)
No Cement	1.38	22.0		
II/4	1.36	21.4	1.57	14.6
V/4	1.37	22.7	1.55	13.8
IP/4	1.38	19.3	1.54	16.7
IIA/4	1.40	21.5	1.55	14.2
II/8	1.41	20.8	1.57	14.4
V/8	1.43	19.2	1.56	15.3
IP/8	1.40	20.7	1.56	14.2
IIA/8	1.40	19.3	1.58	13.5
II/10	1.35	23.4		
V/10	1.38	21.6		
IIA/10	1.36	23.5		
II/14	1.38	23.5		
V/14	1.37	23.8		
IIA/14	1.38	23.5		

^a The Cement percentages are based on dry weight of phosphogypsum

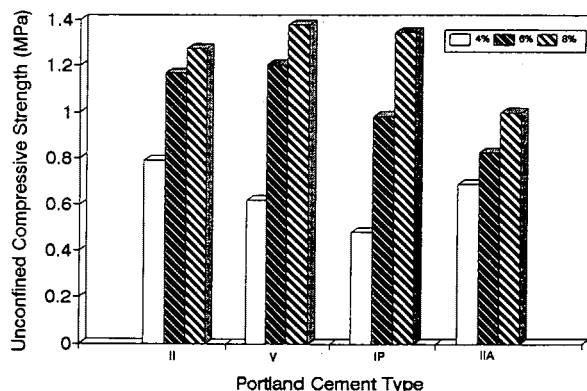


FIGURE 2 Effect of cement type and content on 7-day unconfined compressive strength, standard compaction.

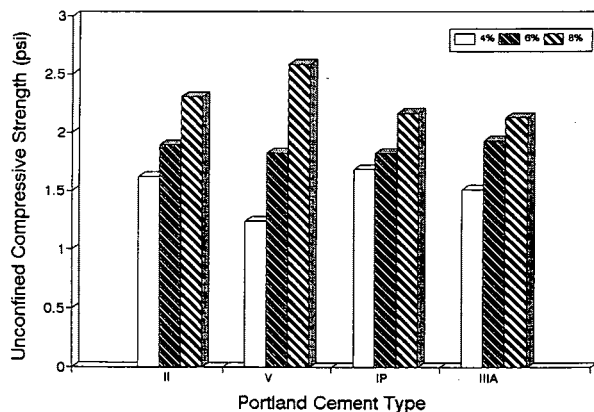


FIGURE 3 Effect of cement type and content on 7-day unconfined compressive strength, modified compaction.

However, the results also showed that the strengths attained at standard Proctor compaction levels and economic cement contents (about 8 percent) were barely adequate in terms of the Louisiana Department of Transportation and Development criterion of 1.7 MPa at 7 days. This strength could be achieved by increasing cement content to more than 14 percent or by increasing the compacted dry unit weight to modified Proctor compaction levels at 4 to 6 percent cement. The practicality of the first is in doubt because of the increased

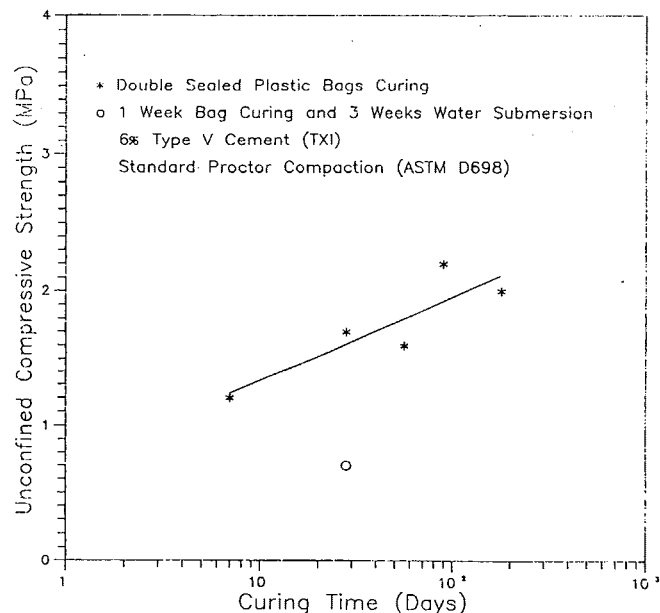


FIGURE 4 Effect of curing time and procedure on unconfined compressive strength.

cost, and of the second because of the difficulty in attaining high compaction levels on the typically soft subgrades of the region.

These results were sufficiently different from earlier studies (12) to suggest that particle-size variability of the phosphogypsum may have an effect. Further studies of this are necessary. However, as small changes in compacted dry unit weight can have a major effect on the unconfined compressive strength (10), this also needs clarification.

It therefore was decided to seek ways of increasing the unconfined compressive strength by the use of secondary additives and to seek to better understand the effects of moisture content and unit weight changes. This required the capability to make samples of controlled unit weight or moisture content. The simple way to achieve this is to move to a constant-volume mold technique, where a known mass of materials is compacted into a known-volume mold. At the same time a means of conserving material and reducing experimental effort was sought. The solution was to adopt the British Standard (BS1924) procedure, using a right cylinder specimen 2 in. in diameter and 4 in. long. The fine grain size of phosphogypsum (75 percent passing #200; Table 2) means that there is no effect of mold size and a saving of 80 percent in material (and effort) between this size specimen and the Proctor mold size is achieved.

ENHANCEMENT OF CSPG MIXES

The second series of tests, therefore, was designed to enhance the program to give a better understanding of the effects of dry unit weight and moisture content, by using the more convenient specimen size with the ability to control unit weight and moisture content separately, and to seek enhanced unconfined compressive strength of the stabilized mixes, by using secondary additives. Mixes that have evident potential for application will then be examined in more detail. In particular, the resilient modulus of the mixes will be determined by repeated loading test for use in mechanistic pavement design procedures.

Density, Moisture Content, and Curing

A limited series of tests was conducted to separate the effects of dry unit weight and moisture content on strength and to look again at the effects of curing. The results are shown in Figures 5 and 6. At constant moisture content it is demonstrated that the strength increases as the dry unit weight increases, and, at constant dry unit weight, it is shown that the strength varies little with moisture content at compaction. The effect of soaking is to reduce strength, but the reduction decreases with increasing dry unit weight or cement content.

High Early Strength Cement

As the strength criterion commonly adopted is applied at 7 days, and because it is known that calcium sulphate retards the set of cement, it was considered that the use of a high early strength (Type III) cement might result in higher 7-day

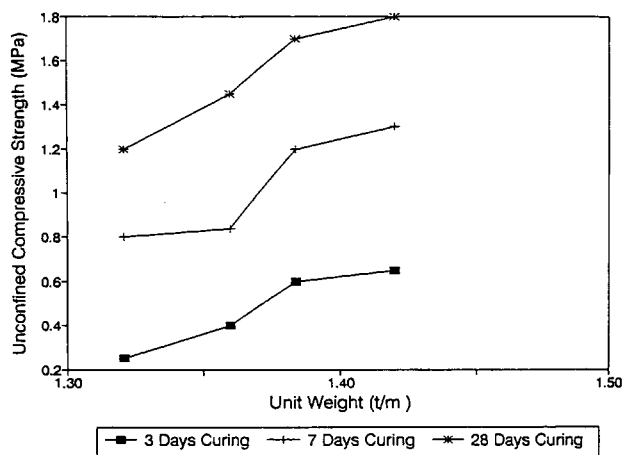


FIGURE 5 Effect of increasing dry unit weight on unconfined compressive strength.

strengths than an ordinary portland cement. The results showed that although 3-day strengths were higher the effect at 7 days was too small to be of practical value (Figure 7).

Secondary Additives

The low early strength suggested that three potential secondary additives should be examined: the use of another mineral component (sand) to improve the grading of the mix, the use of a cement set accelerator (calcium chloride), and the use of a neutralizing agent (hydrated lime) to increase the pH of the mix. The results of the tests are given in Figure 7.

It is evident that lime had little effect, that the sand mixes have evident potential for application, and that calcium chloride was effective at small proportions.

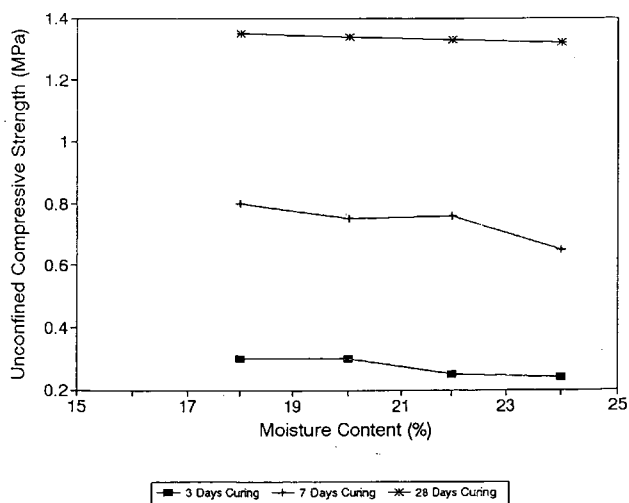


FIGURE 6 Effect of increasing moisture content on unconfined compressive strength.

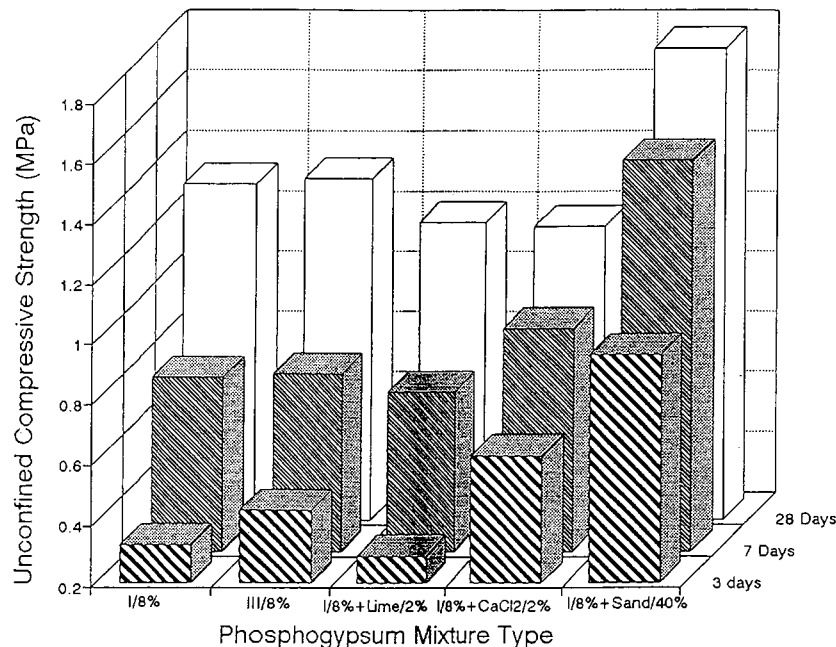


FIGURE 7 Effect of rapid-setting cement (Type III) and secondary additives on unconfined compressive strength.

CONCLUSIONS

Phosphogypsum can be stabilized with cement to produce an adequate material for road base construction to the requirements of the Louisiana Department of Transportation and Development. The final choice of a mix will depend on economics and construction practicability, but the use of more than 14 percent of ordinary portland (Type I) cement will produce adequate strength, as will the use of modified Proctor compaction standards for the construction. The strength can also be increased by the use of an admixture of sand with the phosphogypsum or by the use of a cement set accelerator, calcium chloride. The economics of the various options must now be examined and the experimental program extended for a better knowledge of the effects of the proportions of the various secondary additives and combinations of these additives. Attention must also be turned to the effects of the stabilization process on the permeability and leachability (13) of the compacted stabilized road base materials to determine the possible effects on the environment.

REFERENCES

1. Taha, R., and R. K. Seals. *Applications Identification of Phosphogypsum*. Report I-91-3D. Institute for Recyclable Materials, College of Engineering, Louisiana State University, Baton Rouge, May 1991.
2. Taha, R., and R. K. Seals. *Phosphogypsum Literature Review*. Report I-90-3. Institute for Recyclable Materials, College of Engineering, Louisiana State University, Baton Rouge, March 1991.
3. Ho, R. K. H., and W. H. Zimpfer. Comments on the Investigations of Phosphogypsum for Embankment Construction. *Proc.*, 2nd Workshop on By-Products of the Phosphate Industries, Florida Institute of Phosphate Research, May 1985.
4. Taha, R., and R. K. Seals. *Utilization of FMI's Phosphogypsum in Road Construction—A Review of FMI's Research Results*. Report to Freeport-McMoRan, Inc.; Institute for Recyclable Materials, Louisiana State University, Baton Rouge, April 1990.
5. Gregory, C. A., B. Saylak, and W. B. Ledbetters. The Use of By-Product Phosphogypsum for Road Bases and Subbase. In *Transportation Research Record 998*, TRB, National Research Council, Washington, D.C., 1984.
6. Wong, C., and M. K. Ho. *The Performance of Cement Stabilized Phosphogypsum as Base—State Highway 146, LaPorte, Texas*. Report DHT-11. Texas Department of Highways and Public Transportation, Austin, Oct. 1988.
7. Kenley, W. C., and W. F. Chang. Polk County Experimental Road. *Proc.*, 2nd International Symposium on Phosphogypsum, Florida Institute of Phosphate Research, Vol. 2, 1988.
8. Mo, R. K. M., R. W. Williams, L. L. Cogdill, and W. F. Chang. Columbia County Experimental Road. *Proc.*, 2nd International Symposium on Phosphogypsum, Florida Institute of Phosphate Research, Vol. 2, 1988.
9. May, A., and J. W. Sweeny. Evaluation of Radium and Toxic Element Leaching Characteristic of Florida Phosphogypsum Stockpiles. In *ASTM STP 801*, Atlanta, Ga., April 1985.
10. Metcalf, J. B., and O. G. Ingles. *Soil Stabilization—Principles and Practice*. Butterworths, Sydney, Australia, 1972.
11. Taha, R., R. K. Seals, M. E. Tittlebaum, W. Thornsberry, and J. T. Houston. The Use of By-product Phosphogypsum in Road Construction. Presented at 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 1992.
12. Taha, R., and R. K. Seals. *Expansion Test Specimens—Results and Recommendations*. Report I-91-4D. Institute for Recyclable Materials, College of Engineering, Louisiana State University, Baton Rouge, July 1991.
13. Taha, R., and R. K. Seals. *Engineering Properties and Potential Uses of By-Product Phosphogypsum*. ASCE (in press).

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Laboratory Characterization of Cement-Stabilized Iron-Rich Slag for Reuse in Transportation Facilities

SIBEL PAMUKCU AND AHMET TUNCAN

An iron process residue aggregate referred to as Iron Rich Material (IRM) was characterized and tested in the laboratory to determine its potential as a highway construction material. Cement-mixed and -stabilized products of IRM were subjected to ASTM-based standard tests to determine and compare their strength, permeability, and durability. The potential reuse capacity of IRM was envisioned as aggregate in making stabilized road base, sub-base, or subgrade. The aggregate portion of the material was classified as A-1-b by AASHTO and SW by ASTM. This material was stabilized with cement, lime, and fly ash at varying proportions by weight of the total additives. The resulting products were compacted at their predetermined optimum moisture contents and cured. Then samples of the cured products were tested for unconfined compressive strength, unconfined tensile strength, freeze-thaw durability, and hydraulic conductivity. The best results were obtained with cement-stabilized aggregate for which the 7-day unconfined compressive strength was between 102 and 116 kPa (700 and 800 psi) and the unconfined tensile strength was between 14 and 22 kPa (100 and 150 psi). For these specimens the 12-cycle freeze-thaw test resulted in less than 5 percent material loss. The 45-day cured unconfined compressive strengths of the cement admixture stabilized IRM was over 145 kPa (1,000 psi), which is comparable to approximate strength of 138 kPa (950 psi) of soil cement of sandy gravel with 6 percent cement used in base or subbase courses for heavy traffic. The general conclusion of the work was that the particular residue material, IRM, when stabilized with cement and cementitious substances may be a viable aggregate for reuse in construction of road bases.

The subject of resource recovery and reuse of waste materials has gained much attention within the past decade, principally because of the increased number of environmental statutes and regulations that necessitate the minimization of waste disposal (Comprehensive Environmental Response, Compensation and Liability Act, 96-510, 1980). The benefit of reuse of residual materials of industrial processes should be twofold: (a) compliance with regulations, which helps reduce environmental hazard, and (b) added economy. Effective utilization of these materials as an inexpensive alternative for conventional materials can provide much economy provided that there are no adverse effects to the environment and the created material performs similarly to or equally well as the one it replaces.

Technology for reuse of residue materials needs to be developed independently, aiming at the optimization of the val-

ues of a selected number of physical and chemical properties of the end product. Selection of those properties such as permeability, leachability, strength, rigidity, and durability should depend on the intended function of the end product. First, the residue material should be characterized. Then the products of residue materials that are considered for reuse should comply with the following requirements: (a) minimized solubility and mobility (leachability) of toxic substances, (b) minimized permeability and thus leachability and volume change, and (c) physical stability, strength, and durability. In the United States, compliance with the first requirement is assessed by the Environmental Protection Agency (EPA) extraction procedure toxicity (EPT) or the toxicity characteristic leaching procedure (TCLP) tests (1,2). The physical properties that are often used as indicators of minimized leachability and physical integrity are hydraulic conductivity (permeability), unconfined compressive strength, bulk density, specific gravity, and freeze-thaw and wet-dry durability (3).

The objective of this study was to investigate the possible use of a type of kiln slag produced in Pennsylvania. This slag is a steel industry iron residue classified as a non-hazardous material. It is characterized as Iron Rich Material (IRM) and contains metal iron and iron oxides at about 30 percent by weight. The IRM had already been tested by the standard EPA methods of EPT and TCLP and had passed those tests satisfactorily. The reuse capacities of this material were envisioned as filler/aggregate (in making stabilized road base) or filler/binder (in constructing cut-off slurry walls). To accomplish these objectives, three tasks were proposed. Each constituted a phase of the overall project:

1. Testing the material in the laboratory to investigate its suitability for use in each of the capacity given earlier,
2. Modifying chemically or physically the properties of the material to render it suitable for the needs of each capacity, and
3. Proposing appropriate design criteria for large-scale application.

In this paper, only the investigation of reuse of IRM as aggregate in making road bases is considered. The results of testing for physical characterization of the aggregate slag and the aggregate slag stabilized with admixtures (cement and cement mixtures) are presented and discussed in the following sections.

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INVESTIGATION

Characterization of Aggregate

The aggregate samples received from the source were identified as new and old, on the basis of their age in stockpile. The new material is the fresh slag from the kiln, and the old material is slag that had been stockpiled for approximately 2 years. Both of the slags had been characterized as heterogeneous and vesicular. Mineralogical composition of the slags was determined to be mostly metal iron (Fe) and iron oxides (FeO-wustite, Fe_3O_4 -magnetite, and Fe_2O_3 -hematite), calcium, aluminum and magnesium silicates, and glass. Earlier investigations on the IRM material showed that the metal oxide content of the material was approximately 30 percent by weight (approximately 1 part of iron oxides to 2 parts of crystalline silicates). The specific gravities of the iron oxides present in the IRM slag are near 5.0 and above. The crystalline silicates have average specific gravity of 3.0. Abundance of glass would lower the overall specific gravity of the mineral mixture in the slag.

Gradation

According to Unified Soil Classification System (USCS, ASTM D2488), both of the materials were classified as well-graded or gravelly sand with little or no fines (SW). According to AASHTO specifications, they were classified as A-1-b, the significant constituent materials of which are stone fragments, gravel, and sand. Figure 1 shows the generated gradation curves for these materials along with the soil gradation ranges recommended for bases and subbases by ASTM D448 specifications. ASTM D448 specification gives the upper and lower ranges of gradation sizes for processed aggregate used in road construction. Superimposed on the same graph are the grading requirement ranges for final mixtures of aggregates to be used in construction of bases and subbases according to ASTM

D2940. Both of the slag materials are well graded and have good portions of their components from the large size. The old material contains more large and fine particles than the new material. The increased fines portion may be due to the working of the old material, which could result in crushing and production of more fines. The old material also has a significant portion of large particles above # 4 sieve size, possibly because of the particular processing of the material at the time of production or the agglomeration and cementing of particles with age. Both of the materials appear to comply with ASTM D2940 gradation requirements below 1-mm particles, but the curves need to be pulled down into the range by addition of mid-size coarse material.

Aggregate Index Properties

Table 1 presents a summary of some of the physical and chemical index properties measured for the new and the old aggregates. Each of these measurements represents the average of three or more tests. The bulk specific gravities of the new material were calculated to 2.90 for the fine (passing #4 sieve) and 2.94 for the coarse fractions. These values indicate heavier material than aggregates of rock types such as granite (2.61 to 2.68), limestone (2.59 to 2.71), or sandstone (2.43 to 2.96). The old material was even heavier, with average bulk specific gravity of 3.01. This was attributed partially to oxidation and the formation of iron oxide hydrates (rust or limonite) by aging of the material. Another reason for the difference may be possible variation in the original chemical composition and metal content of the old aggregate slag. The water absorption of the old material was less for both the fine and the coarse portions. This may indicate that the water absorption capacity of this material is partially satisfied by the production of iron compounds.

The unit weight and percentage void space determination was conducted on samples of compacted mixed aggregates. It should be noted that the typical compaction effort used in

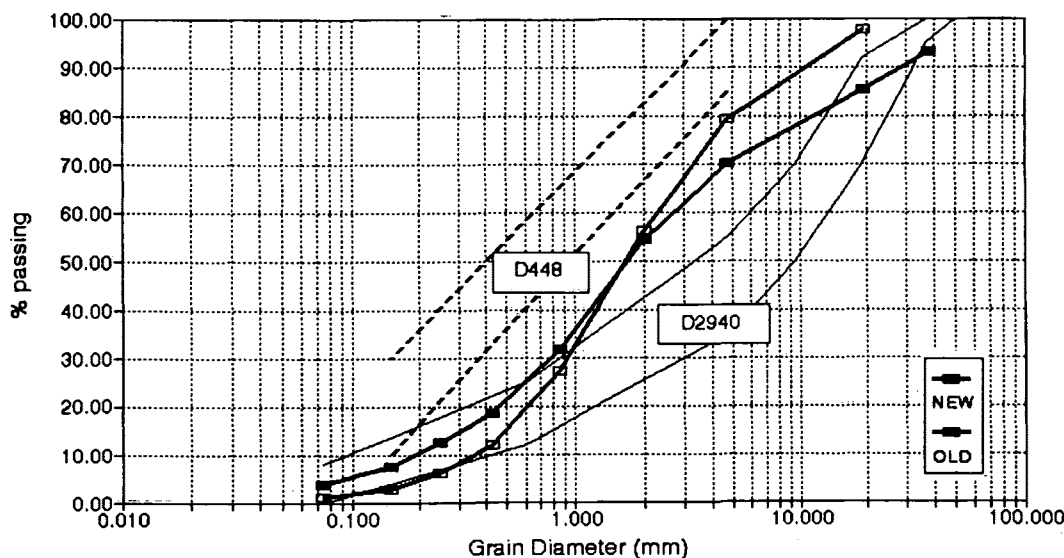


FIGURE 1 Particle-size distribution curves for IRM aggregates.

TABLE 1 Physical Properties of IRM Aggregate

Property	ASTM Procedure	New Aggregate			Old Aggregate		
		Coarse	Fine	Mixed	Coarse	Fine	Mixed
Bulk Specific Gravity (BSG)	C-127 C-128	2.94	2.90		3.00	3.02	
BSG- Saturated Surface Dry	C-127 C-128	3.19	3.18		3.09	3.25	
Water Absorption (%)	C-127 C-128	8.66	9.41		3.0	7.53	
Dry Unit Density (kN/m ³)	C29			18.34			21.57
Void Content (%) (by total volume)	C29			36			27
Void Content (%) (by solid volume)	C29			56			37
Weight Loss of Material (%)	C88 (sulfate soundness)			18.26			19.60
Index of Particle Shape and Texture	D-3398			12			15
Index of Aggregate Durability	D-3744			87			84
CaO content (%) (by weight)				13.9			12.5
Volume Expansion (%)	D4792 N/S ^b			ND ^a 0.044			ND 0.044

a Not Detectable,

b No surcharge

this test is less than the compaction effort used in a standard Proctor (ASTM D698) compaction test, therefore the unit density achieved is less. The void content of the old material was less than the new material. This is attributed to the larger fines portion and to the formation of iron oxide hydrates in the aged slag.

The sodium sulfate soundness test is used to estimate the soundness of aggregates when subjected to weathering action in concrete or other applications. The sulfate soundness test is often considered a rigorous durability test. In many cases, it has been observed that aggregates that do not satisfy the specified requirements by sulfate soundness test do perform well in the field under severe exposures (4). Therefore, the ASTM standard test for freeze-thaw durability (ASTM D666) is often recommended as a check against sulfate soundness test. In the sulfate soundness test, the average total weight losses were estimated at about 18.3 percent for the new material and 19.6 percent for the old material. The observation that these numbers are very close confirms the good repeatability of this particular test.

Particle index is used to indicate the effects of aggregate shape and texture on compaction and strength characteristics of soil-aggregate and asphalt-concrete mixtures (ASTM D3398). This index ranges from 1 to 21. The more angular and rougher the aggregate particles, the higher is this value. It has been shown that the volume of voids in a soil-aggregate mixture of a given gradation under a standard laboratory compaction condition increases more or less linearly with increasing value

of the particle index (5,6). Therefore, the density of a soil-aggregate mixture varies not only with the gradation of the mixture but also with the particle index. The weighted average indexes are 12 for the new material and 15 for the old material. Therefore, the old material is rougher in texture and more angular in shape. These numbers are similar to particle index of crushed stone of bulky, uniform size particles with sharp edges and rough surfaces or gravel with flat particles with sharp edges and rough surfaces. A comparable material designated as glacial gravel with optimum moisture content of 5.8 percent, maximum dry unit weight of 21.8 kN/m³ (138.9 pcf), and a gradation similar to the slag material has a particle index evaluated as 12.1. The angularity and roughness of the particle increases its shearing resistance, but it may also increase its tendency to crush into smaller particles under load. This type of behavior was observed in compaction of both materials, but more significantly in the old material.

The durability index (ASTM D3744) of an aggregate is a value indicating the relative resistance of the aggregate to production of detrimental clay-like fines when subjected to a prescribed mechanical method of degradation. This index ranges from 0 to 100, 0 being complete deterioration and 100 being no deterioration. Both of the aggregates performed well in this test. The durability indexes were 87 and 83 for the new and old materials, respectively.

Expansion tests (ASTM D4792) were conducted with and without surcharge. In the unsurcharged tests, volumetric expansion of 0.044 percent was measured for both the old and

the new materials. The expansion occurred within the first 2 hr of each test and stayed constant for the next 5 days under regulated temperature. No measurable expansion was detected when the materials were surcharged by 10 lb of load, as specified in ASTM D4792. In general, volumetric expansion of soil-aggregate mixtures under 2 percent corresponds to low swelling potential. The measured low expansion is attributed primarily to the low percentage of fines in both of the materials.

The CaO content measurement was conducted to assess the degree of self-hardening of the material and to compare it with other types of calcium containing residue materials. The average CaO content of the new and the old material is about 13 percent by weight. This places the material among the residues bearing moderately high calcium content. Typically, bituminous fly ashes contain 4.5 percent CaO and lime-modified fly ashes contain 33.6 percent CaO by weight.

Moisture-Density Relationships for Aggregate

Standard Proctor test results showed good repeatability for moisture-density relation of the new aggregate. The average optimum moisture content and the average maximum dry unit weight were determined as 5 percent (coefficient of variance = .002) and 21 kN/m³ (133.8 pcf). For the old material, the repeatability of the moisture-density data were not as good

because of the nonuniformity of the portion above #4 sieve. The average optimum moisture content was determined to be 8 percent (coefficient of variance = .01), and the average maximum dry unit weight was 24 kN/m³ (153.2 pcf).

Testing of Aggregate with Admixtures

The IRM slag was mixed with binding agents to improve its physical properties and strength. Three types of admixtures were selected: portland cement, lime, and fly ash. The fly ash was classified as bituminous; lime was commercially obtained hydrated lime (Ca[OH]₂), and cement was Type I portland cement.

The proportions of these admixtures used in mixing with the slag aggregate were either based on recommended proportions by ASTM or selected as trial proportions initially. Three percentages of total admixture were selected as 6, 12, and 18 by dry weight of the aggregate. The relative proportions of each admixture used in these series of tests are given in Table 2. The combinations of admixtures were tested both with the new and the old IRM aggregates. The aggregate portion of each mixture was prepared by mixing the appropriate amounts of various aggregate sizes to achieve a pre-designated gradation curve. This curve was selected to pass through the mid-section of the range of gradation suggested by ASTM D2940 for base and subbase materials. The follow-

TABLE 2 Compressive Strength and Density of Trial Mixtures of New and Old IRM Aggregates with Additives

Percent Additive by Weight			Moisture Density Relationship Optimum Moisture and Maximum Dry Unit Weight				7-day UCS ^a at Optimum Moisture, (kPa)	
Cement	Lime	Flyash	New IRM		Old IRM		New IRM	Old IRM
			ω _{opt} (%)	γ _{dry} (kN/m ³)	ω _{opt} (%)	γ _{dry} (kN/m ³)		
6 %								
2	1	3	11.5	23.9	8.8	27.3	1089.3	1420.2
2	2	2	11.3	23.5	11.0	27.4	1227.1	1627.0
4	1	1	12.5	23.6	9.0	27.3	1158.2	2723.1
12%								
2	4	6	-	-	11.0	26.5	-	875.5
2	5	5	13.0	24.2	10.6	27.0	861.8	1482.2
2	6	4	13.0	24.7	11.0	26.5	1096.1	586.0
4	2	6	12.0	24.8	10.0	27.0	1709.7	2275.0
4	4	4	12.3	25.0	11.3	26.2	2426.7	1702.8
4	6	2	13.0	24.2	11.0	27.0	1833.8	2151.0
6	2	4	11.0	24.9	10.0	27.5	4136.4	3722.8
6	3	3	12.0	24.6	10.0	27.2	4184.7	4839.6
6	4	2	12.0	23.7	10.9	27.9	3888.2	4081.2
18 %								
2	4	12	12.0	24.2	10.0	25.7	875.5	668.7
2	8	8	14.0	23.1	11.8	25.5	923.8	1123.7
2	12	4	14.5	23.1	12.8	25.1	717.0	372.3
4	6	8	12.0	23.4	11.0	25.7	2144.0	1992.3
4	7	7	13.5	23.2	10.8	24.5	2330.2	2393.3
4	8	6	11.5	23.2	12.7	24.4	2764.5	3095.4
6	3	9	11.6	24.1	10.8	24.6	2854.1	2854.1
6	4	8	11.5	24.1	11.8	24.0	4370.8	3729.7
6	6	6	12.3	24.0	11.5	24.7	4832.7	4295.0
6	8	4	13.5	23.6	12.3	25.0	3943.4	3784.8
6	9	3	14.0	23.0	11.8	24.7	3722.8	3516.0

a Unconfined compressive strength

ing tests were conducted on the laboratory-mixed specimens in duplicate:

1. Moisture density: ASTM D558 and ASTM D698,
2. Unconfined compressive strength: ASTM C593 (7, 28, and 45 days cured),
4. Hydraulic conductivity: ASTM D5084 (7 days cured), and
5. Freeze-thaw durability: ASTM D593 (7 days cured).

The strength, permeability, and durability tests were conducted on samples of each mixture prepared at their optimum moisture content as determined from the moisture-density relation tests. All samples were cured in airtight plastic bags for the appropriate duration before testing. Table 2 gives a summary of the results pertaining to these tests of the 7-day cured old and new aggregate mixtures.

Moisture-Density Relationships for Aggregate plus Binder

The mixtures were molded in a Standard Proctor compaction mold and tested to determine optimum moisture and maximum dry unit weight according to ASTM D698 and D1557. As observed from the data, maximum dry unit weights did not change significantly for the two materials with the additives. The average maximum dry unit weights are on the order of 25 kN/m³ (159 pcf) for the new material mixtures and 26 kN/m³ (165 pcf) for the old material mixtures. The optimum moisture contents for the new material mixtures are consistently higher than the old material mixtures, although not significantly different, being on the order of 12 percent.

The maximum dry unit weight values of 25 and 26 kN/m³ fall within the high range for typical aggregates mixed with binders (7,8). Typically, well-graded crushed stone mixed with lime and fly ash at the lime:fly ash (L:FA) ratio of 1:4 has maximum dry unit weight on the order of 22 kN/m³ (143 pcf). Similarly, lime-treated river gravel and medium sand would exhibit 21.5 and 19 kN/m³ (137 and 122 pcf) of maximum dry unit weight, respectively. The relatively higher values are due to the higher specific gravity of the IRM aggregates (average specific gravity = 2.95) than the typical soil aggregates. Therefore the increased unit weight does not necessarily indicate a higher degree of compaction for the IRM aggregate mixtures.

Unconfined Compressive Strength

ASTM suggests that the minimum 7-day cured compressive strength of a stabilized aggregate/soil system be 2760 kPa (400 psi) (ASTM C593) (10). Observing from Table 2, the mixtures that meet or come close to the strength value as specified are the aggregate/cement and the aggregate/cement, lime, fly ash (CLFA) mixtures. The 6 percent admixture specimens exhibit low strengths consistently. The specimens of the mixtures that show the highest 7-day strengths are cured up to 45 days and tested for compressive strength.

The results of strength tests on longer cured specimens of both the new and the old IRM slag mixed with 12 and 18 percent admixture are presented in Table 3. The values reported in this table are corrected by the strength correction factor of 0.94 for specimen length/diameter ratio of 1.25 used in this work (ASTM C42). The highest 45-day cured strengths were achieved with the 12 percent total admixture specimens

TABLE 3 Compressive Strength of Long-Term Cured Samples of Selected Mixtures of New and Old IRM Aggregates with Additives

Percent Additive by Weight			Unconfined Compressive Strength at Optimum Moisture (kPa) ^a					
Cement	Lime	Flyash	7 days		28 days		45 days	
			New IRM	Old IRM	New IRM	Old IRM	New IRM	Old IRM
12 %								
4	4	4	2282.0	1599.4	2702.4	2897.1	4177.8	6494.1
6	2	4	3888.2	3502.1	6942.3	5584.1	8603.7	7004.3
6	3	3	3936.5	4550.0	5487.6	5735.8	7052.6	7176.7
6	4	2	3660.7	3833.0	5901.3	6246.0	6645.8	7742.0
18 %								
4	7	7	2192.3	2247.4	5329.1	4880.9	6190.8	5287.7
4	8	6	2337.1	2909.2	2599.0	3853.7	6314.9	4384.6
6	3	9	2681.7	2681.7	4267.4	3626.2	5287.7	3729.7
6	6	6	4543.1	4039.9	5887.5	6218.4	7790.2	8072.9
6	9	3	3502.1	3302.2	4177.8	5391.1	5777.2	6149.4

^a Strength values are corrected by a factor of 0.94 for specimen L/D ratio of 1.25

of either aggregate, ranging from 4136 kPa (600 psi) to over 8273 kPa (1,200 psi). The specimens that exhibited 28-day to 7-day strength ratios close to 2 were the aggregate/CLFA mixtures at C:L:FA percentages of 6:2:4, 6:4:2, and 6:6:6.

The variation of unconfined compressive strength with duration of curing are presented in Figures 2 and 3 for the new and the old IRM aggregate mixtures of 12 percent total admixture, respectively. In the overall analysis, the highest strength was achieved with the new aggregate when it was mixed with 12 percent CLFA at a 6:2:4 ratio. The old aggregate required more lime for improved strength with the 12 percent admixture. This is probably due to the slightly less CaO content of the old aggregate initially. The best strength was obtained with a CLFA ratio of 6:4:2 with the old aggregate. For either of the aggregates, lime or fly ash in excess of 6 percent caused strength reduction. This effect was more pronounced with excess fly ash. This was probably due to the unreacting bituminous nature of the particular fly ash used, which did not let it be incorporated in the cemented matrix when applied in excess (8).

Hydraulic Conductivity Tests

The 7-day cured specimens of the mixtures compacted at their optimum moisture contents were subjected to a Constant Rate of Flow Flexible Wall Permeameter Test (ASTM D5084). The specimens were water-saturated under a confining pressure of 34 kPa (5 psi), and the coefficients of hydraulic conductivity

were measured at constant rate of flow of water under. The coefficient of hydraulic conductivity for the unstabilized control specimens were on the order of 10^{-2} cm/sec, whereas for the stabilized specimens it ranged from approximately 10^{-4} to 10^{-5} cm/sec for all the mixtures tested. This range places the stabilized material in the category of moderate to low permeability systems. The lowest hydraulic conductivities were measured for the aggregate and LFA mixtures, and the highest permeabilities were measured for the aggregate and cement mixtures.

The hydraulic conductivity measurements can be useful in judging erodibility and frost susceptibility of earthen materials. Low permeabilities may indicate low potential for erosion, frost heave and leaching of material, since water inflow is restricted and the quantity of water available for frost formation may be less (7,8).

Durability Tests: Freeze-Thaw

The cumulative percentage weight loss per cycle of freeze-thaw is presented for four specimens in Figure 4. As observed, the maximum weight loss occurred for the new aggregate and CLFA mixture. The average weight loss for the samples of this mixture was 10 percent at the end of the 12th cycle; the others showed total weight losses of about 4 percent at the end of the 12th cycle. The standard durability criterion for typical admixture-stabilized bases and subbases ranges from 10 to 14 percent maximum weight loss (i.e., ASTM, FAA,

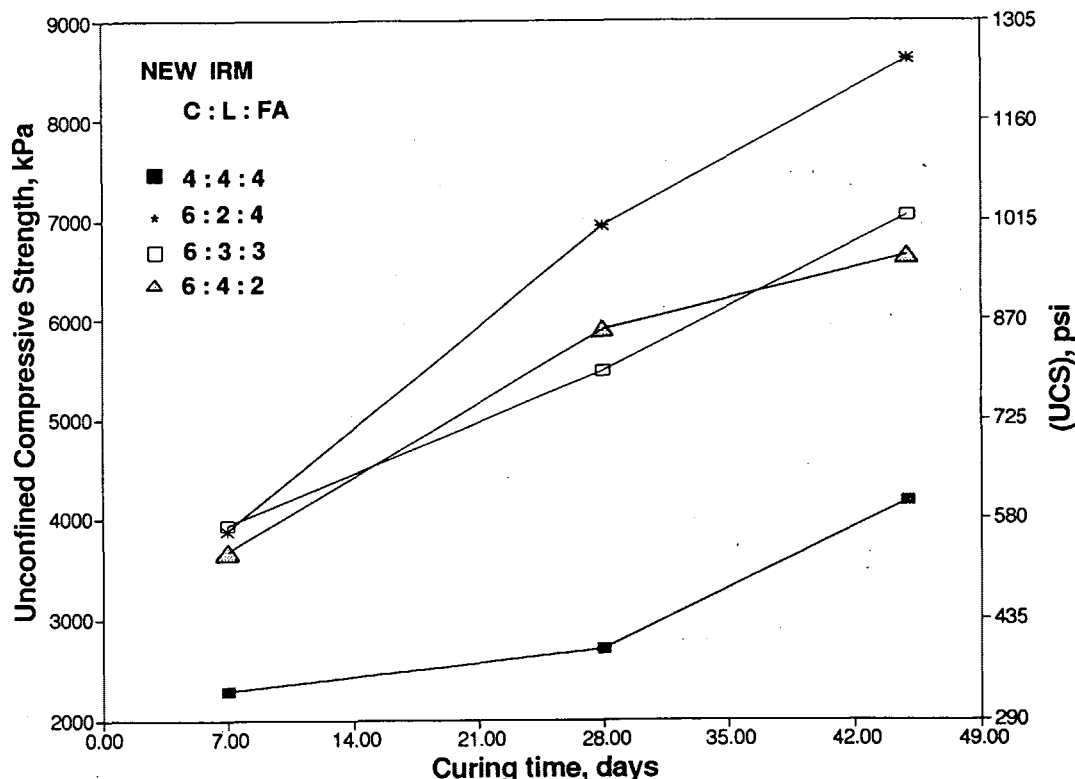


FIGURE 2 Unconfined compressive strength versus curing time variation for new IRM mixtures with cement, lime, and fly ash (12 percent total additive by weight).

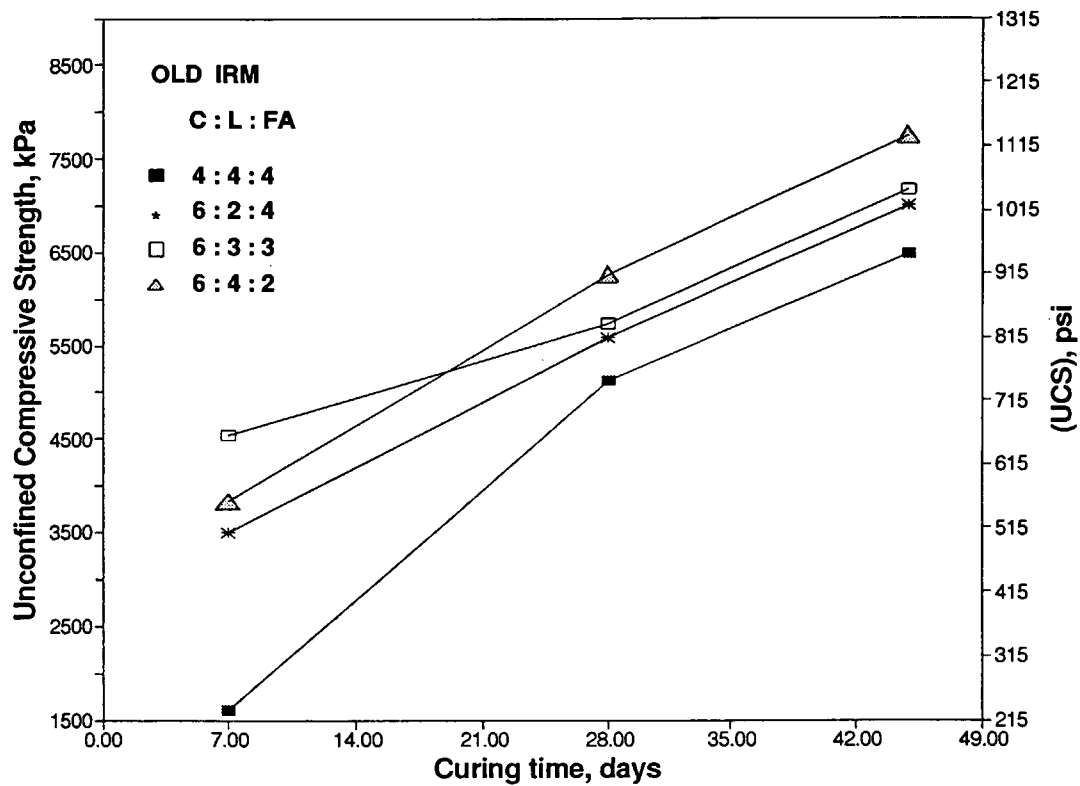


FIGURE 3 Unconfined compressive strength versus curing time variation for old IRM mixtures with cement, lime, and fly ash (12 percent total additive by weight).

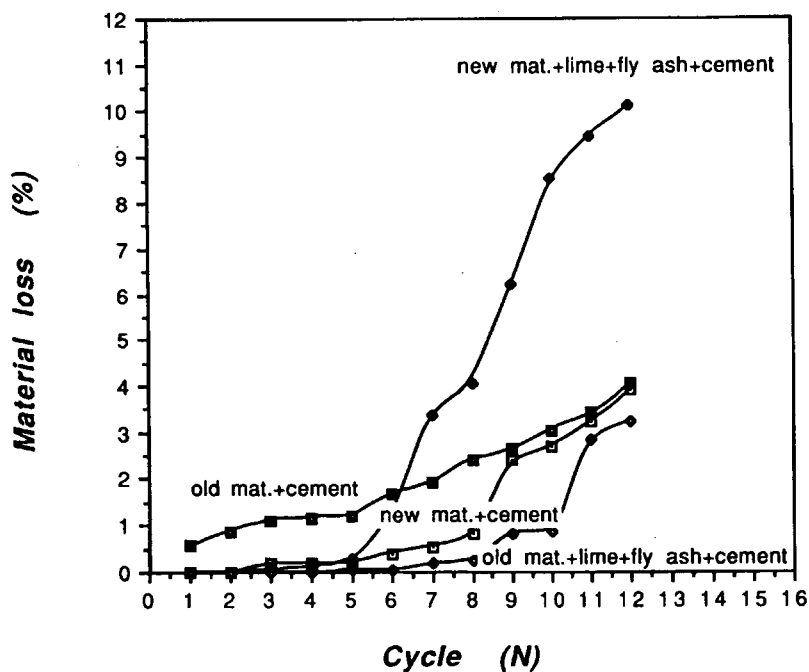


FIGURE 4 Material loss versus freeze-thaw cycles of stabilized new and old IRM aggregates.

Illinois DOT, Pennsylvania DOT). The weight loss values obtained for the materials tested in here are either at or well below this criterion. It appears that the cement-stabilized aggregates, both new and old, best satisfy the durability criterion. The ratio of the unconfined compressive strength after and before the freeze-thaw were also determined. The highest ratio was 0.68, which was exhibited by the new aggregate/cement mixture. The average of this ratio for the aggregate/CLFA mixtures was 0.35.

DISCUSSION OF RESULTS

As stated earlier, the primary objective of the experimental work, results of which presented here was to investigate the feasibility of using the iron-rich kiln residue in a typical cement-stabilized earth construction. The two possible applications envisioned were use of the aggregate portion in stabilized road subgrade or subbase/base construction. The end product of the investigation was recommendations for design mix formulas of these materials and admixtures to be used in the capacities stated earlier.

IRM Aggregate in Stabilized Road Subgrade, Subbase, or Base

The IRM aggregates were classified as A-1-b type, according to the AASHTO classification system. Subgrade characteristics such as subgrade modulus, k ; California bearing ratio (CBR); and resistance value, R are determined through field or laboratory tests. For light traffic conditions, broad relationships between soil classification and these parameters can be used to estimate the subgrade strength (10). Accordingly, the minimum modulus of subgrade reaction for A-1-b soils is 68 MPa/m (250 psi/in.), and the minimum CBR value is 25. The optimum moisture content and maximum dry density of a typical nonplastic well-graded sand with 2 percent clay content are 7 percent and 21.2 kN/m³, respectively (11). These values compare well with the 5 percent, 21 kN/m³ and 8 percent, 24 kN/m³ for the new and the old aggregate measured in standard Proctor test. The C:L:FA mixed IRM may also be considered for construction of modified subgrades. In such cases, recommendations on determining minimum compacted thickness of modified subgrades (12) may be used as guide lines to establish protocol for use of IRM in subgrade applications.

Subbase or Base Characteristics of IRM

If the CLFA modified IRM is considered for construction of base and subbase courses, thickness design procedures established for soil-cement (10) or soil-lime: fly ash layers (13) may be used as guidelines to develop specific protocol to IRM in such applications. This is suggested by the similarities between some of the mechanical properties of the soil-cement, soil-lime, and fly ash layers and the modified IRM material.

CONCLUSIONS

This paper presents the results of a two-phase work to establish the feasibility of using an iron-rich kiln slag (IRM) produced in Pennsylvania in construction of earthen structures. In the first phase, the IRM slag was characterized physically and some preliminary tests were conducted to establish its potential for construction material when stabilized with binders. In the second phase, admixture modification of the aggregate (IRM) was undertaken to obtain suitable physical properties of the final products to use them in construction of stabilized road subgrade or base/subbase courses. The general conclusion of the work is that the iron-rich kiln slag tested in this program may be a viable material for reuse in construction of highway earthen structures. However, further investigations are recommended to establish field performance of the stabilized aggregate in a typical road base.

The admixture modification of the pregraded aggregate showed that addition of cement at 6 percent by dry weight of the aggregate produced 7-day cured strengths above the National Ash Association recommended value of 400 psi for aggregate mixtures stabilized with cement, lime, and fly ash. Addition of either lime or fly ash in excess of 6 percent resulted in lower strengths and poor strength increase with curing time. The best results with respect to the final 45-day strength and also with respect to strength increase with curing time were achieved with addition of cement, lime, and fly ash at the ratios of 6:4:2; 6:2:4; 6:3:3, and 6:6:6 for both the fresh (new) and the aged (2 years old). The average 45-day cured unconfined compressive strength value of these specimens was 158 kPa (1090 psi), which is comparable to approximate strength of 138 kPa (950 psi) for soil-cement of sandy gravel and 6 percent cement. The 45-day strength achieved is also above the typically recommended value for soil-cement layers used in base or subbase courses for either light or heavy traffic.

ACKNOWLEDGMENTS

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REFERENCES

1. Environmental Protection Agency. *EP Toxicity Test Procedure*. 40 C.F.R., Part 261.24, Appendix 2, 1980.
2. Environmental Protection Agency. *Federal Register* 51, No. 114, June 13, 1986.
3. Conner, J. R. *Chemical Fixation and Solidification of Hazardous Wastes*. Van Nostrand Reinhold, New York, 1990.
4. Baker, R. F. *Handbook of Highway Engineering*. Van Nostrand Reinhold, New York, 1975.
5. Huang, E. Y. A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles. *Proc., ASTM*, Vol. 62, 1962, pp. 1223-1242.
6. Huang, E. Y., A. Auer, and R. P. Triffo. Effect of Geometric Characteristics of Coarse Aggregates on Strength of Soil-Aggregate Mixtures. *Proc., ASTM*, Vol. 64, 1964, pp. 922-933.

7. Ingles, O. G., and J. B. Metcalf. *Soil Stabilization: Principles and Practice*. Butterworths, Sydney, Australia, 1972.
8. Winterkorn, H. F., and S. Pamukcu. Soil Stabilization and Grouting. In *Foundation Engineering Handbook*, 2nd ed., Van Nostrand Reinhold, New York, 1991.
9. GAI Consultants, Inc. *Guide for the Design and Construction of Cement-Stabilized Fly Ash Pavements*. Process and Technical Data Publication. National Ash Association, 1976.
10. Thickness Design for Soil Cement Pavements. *Engineering Bulletin*, Portland Cement Association, 1970.
11. Rico, A. R., H. del Castillo, and G. F. Sowers. *Soil Mechanics in Highway Engineering*. Trans Tech Publications, Germany, 1988.
12. Soil Testing Services, Inc. *Thickness Design Procedure for Airfields Containing Stabilized Pavement Components*. Final Report. Contract ARDS-486. FAA, U.S. Department of Transportation, 1964.
13. Myers, J. F., R. Pichumani, and B. S. Kapples. *Fly Ash as Construction Material for Highways: A Manual*. Report HWA-IP-76-16. GAI Consultants, Inc.; FHWA, U.S. Department of Transportation, May 1976.

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Control and Prevention of Asbestos Exposure from Construction in Naturally Occurring Asbestos

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Construction projects in Fairfax County, Virginia, routinely disturb amphibole mineral deposits causing actinolite asbestos and tremolite asbestos fibers to become airborne. These same mineral formations exist extensively on the east and west coasts of the United States. Asbestos is regulated by federal, state, and local authorities as a proven human carcinogen. The air-monitoring data presented in this paper show that construction projects in naturally occurring asbestos can produce asbestos exposures to workers and the public. These construction projects can be monitored using standard airborne fiber sampling and analysis techniques, National Institute of Occupational Safety and Health (NIOSH) 7400, and the Occupational Safety and Health Administration (OSHA) reference methods. Exposure to asbestos can create a significant, long-term, liability problem unless prudent actions are taken by responsible parties to prevent asbestos fibers from becoming airborne. The regulations created by the Fairfax County Air Pollution Control Division (APCD) and OSHA 29 CFR 1926.58 are reviewed. The Fairfax County Air Pollution Control Division Control Requirement Directives 1 and 2 are designed to control fugitive dust, establish air monitoring, and require safe disposal and covering of soil. The effective work practices used to control fugitive asbestos emissions from the construction projects are discussed. Construction projects can safely be completed if these regulations and work practices are followed.

The presence of naturally occurring asbestos mineral deposits in Fairfax County, Virginia, was brought to the attention of the Fairfax County Air Pollution Control Division (Fairfax APCD) in 1987. During the building boom of the late 1980s, the first deposits of asbestos rock were discovered at a construction project for an underground parking garage. This project encountered a large vein of tremolite asbestos. As a result of the rock being drilled and crushed, dust covered the entire construction project. Several air drill operators began experiencing itching and skin irritation. After medical and geological investigations, it was determined that the irritation was caused by tremolite asbestos fibers.

State and local agencies are treating the actinolite or tremolite minerals as asbestos-containing material because significant fibrous constituents coexist in a heterogeneous mix with the nonfibrous portion of the rock. The rock produces airborne fiber particles as a result of mechanical deformation. Air-monitoring data, obtained from different construction sites, reflect actual exposure to asbestos fibers during documented

work activities. The monitoring data presented in this paper reflect both personal and ambient conditions under which the standards are exceeded.

In addition to a number of construction projects in the county, there are currently several projects involving actinolite or tremolite mineral deposits. The construction and development in these deposits have presented significant challenges to public and employee safety. Air-monitoring data confirm that, as a result of the construction activity, a potential health hazard to the public and workers exists. Violations of the ambient and personal asbestos exposure standards have occurred even while using good wet control methods to control dust. Consequently, employees must have personal protective equipment to avoid asbestos exposure. The violations have necessitated the control and prevention of asbestos exposure from naturally occurring asbestos construction projects.

NATURALLY OCCURRING ASBESTOS: A NATIONAL PROBLEM

Large areas of the United States have asbestiform mineral deposits. These deposits exist as serpentine or amphibole in greenstone and ultramafic rock formations and vary greatly in concentration of their asbestos. California has large land areas of serpentine formations. These areas contain quarries that have serpentine, chrysotile asbestos. The East Coast contains veins of serpentine and amphibole rock formations that stretch from Canada to Georgia (1).

In Fairfax County actinolite and tremolite minerals exist in massive rock formations. The soil layer for these areas runs only 2 to 3 ft deep before striking bedrock. These same conditions may not exist in all areas of the United States. The concentration of asbestos fiber in these mineral deposits can vary from 0 to more than 95 percent as determined by several bulk analysis methods including polarized light microscopy (PLM), X-ray diffraction (XRD) and transmission electron microscopy (TEM). The Fairfax County Soil Science Office conducted a study of randomly selected rocks along the 28.2 km² (10.9 mi²) vein, identified as the Piney Branch Complex (2). The average asbestos fiber concentration of the rock, as determined by PLM and TEM analysis, was 38 percent. Thirty-three samples were collected, which ranged from 85 percent to 0 percent. Other samples collected during the last 3 years and analyzed by TEM, XRD, and PLM have yielded comparable, significant asbestos fiber contents.

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In an undisturbed natural environment, these fibers are locked in place within the rock and represent no health hazard. However, when disturbed, for example during construction, these fibers are released as a fine dust that can readily be inhaled into the respiratory system. Long-term exposure to such conditions could lead to debilitating or fatal diseases. Dry, windy conditions could carry this hazardous dust beyond the boundaries of a construction site. Individuals, whose only connection with the site is their proximity to it, could be exposed to a serious health hazard.

The Piney Branch Complex trends northeast to southwest through the county from northwestern Fairfax City to the Occoquan River west of Clifton. The asbestiform minerals found within this portion of the formation form long, strong, flexible fibers that can be separated into bundles or subdivided into progressively finer needle-like fibers. Smaller areas of the Piney Branch Complex occur to the north. The asbestiform minerals in these units may contain chrysotile, as well as actinolite and tremolite. This formation is generally found associated with the soil group referred to as the "orange soil" series. This soil group is formed in weathered materials from mixed basic and acid rock of the Piedmont Uplands creating a plastic clay. The orange soils series serves as a marker for the actinolite and tremolite bedrock beneath the clay (3).

The fibrous or asbestos forms of actinolite and tremolite minerals are likely to occur in localized areas along zones of extreme deformation (such as faulting and folding). These localized areas include fibrous veins readily observable with the unaided eye and adjacent bedrock that is generally a heterogeneous mixture of fibrous forms and nonfibrous forms of the parent minerals. Various mineralogical forms are found, including prismatic, acicular, and asbestiform, with dramatic heterogeneity throughout the region and even within individual projects. The localized concentrations are difficult to identify before rock excavation. Therefore, all areas within the Piney Branch Complex are treated as a potential site for asbestos.

Consultations with various professionals including mineralogists, geologists, soil scientists, and petrologists experienced in asbestos mineral study have supported the view that undisturbed soil overlying asbestos-laden bedrock is unlikely to contain appreciable amounts of asbestos. Two fundamental principles provide the basis for this position. First, in the weathering process, actinolite and tremolite minerals, as well as antigorite and chrysotile are known to transform into clay mineral. Second, there is no recognized transport mechanism that accounts for asbestos mineral migration from the underlying bedrock into the upper soil horizons without mechanical disturbance. However, soils in construction areas may contain asbestos if the underlying asbestos-containing rock has been disturbed and incorporated into the soil, or if asbestos-containing rock has been deposited on the site.

Actinolite or tremolite may occur in the transition layers of the soil. These clays have no connection with the traditional Virginia red clay. The reference to "orange" bears no relationship to its actual color, which is a yellow brown to olive. The orange soil series is used as an indicator for the location of the Piney Branch Complex. The rock formation in the Piney Branch Complex is typically olive-green to blue-green in color, with varying degrees of hardness and concentrations of asbestos fibers. The map of major problem soils areas

issued by the County of Fairfax (4) identifies the location of the orange soil series and where it is assumed the rock formation contains asbestos fibers. These areas are widely dispersed in the northern part of the county bordering Maryland along the Potomac River. A well-defined area of this soil group also runs through the southwestern portion of the county that borders on Prince William County along Bull Run. The Fairfax County soils map makes it possible to accurately predict the potential sites for asbestos-containing areas.

FIBER, CANCER, AND LIABILITY

Originally, the commercial use of asbestos required fiber characteristics of strength and durability. This is reflected in the geological or mineralogical definition of asbestos. The perspective of OSHA and the Environmental Protection Agency (EPA) asbestos regulations has always been based on health effects. NIOSH has stated their position that asbestos has "no safe exposure level." It must be understood that asbestos is one of a handful of substances conclusively proven to be a human carcinogen. OSHA defines fiber in 29 CFR 1926.58 (b) as "a particulate form of asbestos, five micrometers or longer, with a length-to-diameter ratio of at least 3 to 1."

Naturally contaminated materials pose a significant threat and there is no technically feasible way to separate "the safe from the bad" during the construction process. Federal, state and local agencies use the term asbestos to determine if a material in question is regulated. Once the material meets the chemical, size, and shape criteria for asbestos, then all the material is treated as asbestos and regulated.

Recent medical research from Europe and the United States documents evidence that tremolite asbestos fiber is a more potent carcinogen than chrysotile asbestos (5). It is well known that crocidolite, amosite, and anthophyllite, which are also in the amphibole family of asbestos, are powerful carcinogens. The amphibole fibers are very durable and account for the concern about tumor formation. Tremolite has been found in the lung tissue of tumor victims who were thought to have been exposed only to chrysotile. The victims were exposed to chrysotile contaminated with 1 to 3 percent tremolite (5).

EPA has mandated that state and local air pollution agencies conduct particulate sampling based on the PM-10 Standard, 40 CFR 50.6 (c). This standard measures particles with an aerodynamic diameter less than or equal to a nominal 10 μm according to the method required in 40 CFR 50, Appendix J, and 40 CFR 53.40. Research has shown that particles that are 10 μm or smaller pose a greater health risk because of their ability to penetrate and remain in the lung (6). Serpentine and amphibole asbestos particulate with an aerodynamic size of 10 microns or less should therefore be considered a respiratory hazard.

REGULATORY APPROACH IN FAIRFAX COUNTY, VIRGINIA

Construction in the asbestos soil regions of Fairfax County involves a two-stage approach. The Fairfax County Health Department, Fairfax APCD is concerned with the potential public exposure to asbestos fibers during construction. They enforce the Fairfax APCD Control Requirement Directives 1 and 2 for Construction Activities in Actinolite/Tremolite

Soil Sources (CRD 1 and 2). The Virginia Department of Labor and Industry (VDLI), Occupational Health Division, regulates the interior of the construction site as it pertains to employee exposure. The interior of the construction site is regulated by the Asbestos Standard, 29 CFR 1926.58. These two agencies work in concert to control the emissions of asbestos fibers during work activities.

Contractors are required to comply with the Fairfax APCD standards in CRD 1 for construction work in areas of Fairfax County that contain actinolite or tremolite mineral deposits. The following is a summary of the Fairfax APCD CRD 1, which is the heart of the regulatory approach to protecting the public health.

1. Dust control must be practiced at all times.
2. Air monitoring of the construction site must be conducted during all phases of earthwork involving actinolite- or tremolite-containing material, and comply with the ambient air concentration standard for asbestos.
3. An appropriate, safe, disposal site must be used to dispose of actinolite- or tremolite-contaminated spoils whether removed or not removed from the construction site. All final disposal areas and the finished grade of the developed land shall be covered with 6 in. of clean compacted material.
4. Sufficient notice of asbestos shall be given to all employees and contractors on the site in compliance with the OSHA Asbestos Standard (29 CFR 1926.58).

Personal and ambient air monitoring are conducted according to the NIOSH 7400 method. The personal air monitoring required by OSHA regulation 29 CFR 1926.58 (f) measures the concentrations of asbestos particulate in the direct breathing zone of the employee. The OSHA regulation 29 Part 1926.58 (c) states that no employee may be exposed to an asbestos fiber concentration of greater than the personal exposure limit (PEL) of 0.2 fibers/cm³ (f/cm³) of air in an 8-hr time-weighted average. These personal samples are used in evaluating the fiber releases from specific work activities. The ambient air monitoring is required by Fairfax APCD CRD 1 and is used to determine the public's exposure to asbestos beyond the construction project boundaries. The ambient air concentration standard for asbestos is expressed as a 24-hr average that is not to exceed 0.020 (f/cm³) of air. These samples are measured by monitors at points demarcating public areas from the construction site.

Employees must be informed when the potential for asbestos is present at their work site, and they must be given asbestos awareness training. Employers must establish regulated areas where asbestos fibers can reasonably be expected to exceed the OSHA PEL for workers. Warning signs must be posted to identify regulated areas and warn the public of potential hazards. Employers with a regulated area on multi-employer work sites must inform all employers of the nature and requirements of their regulated areas.

CONTROL PRACTICES

Asbestos mineral formations are encountered by construction activities other than the mining and stone industries. The mining and stone industries choose to work low asbestos content formations, whereas the construction industries are work-

ing in these asbestos formations for purposes unrelated to the asbestos content of the excavated spoils. The OSHA Construction Industry Standards are not limited to the mining or stone industries. The VDLI regulation for Licensed Asbestos Contractor Notification, Asbestos Project Permits and Permit Fees Section 1, Definitions, define "construction" as

... all the on-site work done in buildings or altering structures from land clearance through completion, including excavation, erection, and the assembly and installation of components and equipment.

Construction has not been banned in the Piney Branch Complex because it has been demonstrated that common-sense controls can prevent asbestos exposure. Although it is not practical to create a negative pressure enclosure over naturally occurring asbestos construction sites, it is possible to

1. Implement dust control practices that use water;
2. Establish regulated areas where there is a potential to exceed the PEL;
3. Establish an additional controlled area to limit access to the construction site by the "competent person";
4. Implement decontamination procedures for workers and equipment;
5. Establish positive and documented notification procedures among owners, employers, employees, contractors, and subcontractors in regulated and controlled areas; and
6. Post proper signs so that workers and the public are positively notified of the potential hazards for regulated and controlled areas.

Water is the key to controlling the fugitive dust and thus asbestos emissions from these operations. Application techniques vary from a sophisticated spray system attached directly to the rock-cutting or drilling equipment, to strategically aiming a water hose at a work activity or employing a water truck to spray the entire work area and haul roads. All exposed and excavated material must be kept damp to prevent the release of asbestos fibers into the air. The variable rate fogger nozzles employed in fighting petroleum fires are an excellent tool for this purpose. The fogger nozzle produces a wet mist that knocks down airborne fibers, and water consumption can be controlled by the operator.

The operation of tracked air drills and rock saws in an actinolite or tremolite mineral deposit has great potential to cause the OSHA PEL to be exceeded. Therefore, these work areas must be designated as regulated areas with proper implementation of the Asbestos Standard. Other activities that have produced high airborne fiber concentrations include truck loading, excavating, blasting, grading, and vehicle movement on interior project dirt roads.

Contractors must therefore establish a regulated area where asbestos fibers can reasonably be expected to exceed the PEL. Employees in a regulated area must wear personal protection equipment provided by the employer, including properly fitted and tested respirators and clothing. There must be facilities for decontamination of workers before they leave the regulated areas at the construction site. Decontamination trailers with showers and changing rooms have been installed on construction sites. Here, workers can dress in personal

protective equipment before entering the site and can remove personal protective equipment and shower before going home for the day. This prevents contamination of street clothing and reduces secondary exposure. Disposal of contaminated Tyvek suits and other items are handled in the same manner as they are at abatement projects. Items are placed in approved sealed containers with proper signage and deposited in approved landfills.

The creation of controlled areas prevents unauthorized or uninformed individuals from entering the construction site and risking accidental exposure to asbestos. If an individual did enter the site and allege exposure, the owner and contractors could be held liable and subject to civil suit. This is the reasoning for the notifications in Items 5 and 6 previously listed and required by 29 CFR 1926.58 (*d* and *k*). The certified industrial hygienist or consultant would control access to the construction project, provide awareness training, and determine the employee's level of personal protection equipment. Tyvek suits or suitable protective clothing, along with appropriate respiratory protection, should be worn by workers inside project boundaries if earth and rock have been disturbed, even though they will not be entering a regulated area.

In addition, all tools, vehicles, and equipment should be thoroughly decontaminated before they leave the construction site. Appropriate methods of employee decontamination are similar to those for other asbestos abatement projects. Construction equipment should be decontaminated using fire hoses before removal from the construction site.

Large amounts of asbestos-contaminated rock spoils are generated during construction in the asbestos soil areas. Disposition and transport of these spoils is of particular concern because of the potential release of fugitive asbestos dust and future development of the disposal or fill areas. Identification of safe disposal sites for contaminated material presents challenges for the construction industry as well as landfill operators. Landfill operators have been reluctant to accept spoils because they contain asbestos and occupy large volumes of landfill space. During recent construction of an Interstate access ramp, more than 25,000 m³ of highly contaminated material were moved to a large, tree-covered interchange median. A small hill was created among the trees, covered with clean fill and planted with covering grasses. On another construction project aesthetic berms and changes to the final grade solved the problem of disposal. Construction planning and design should include the disposal of prior spoils.

Trucking of contaminated spoils can be handled in a safe manner. Water or other wetting and binding agents can be used to successfully transport these spoils in a dust-free way. Developed lots should have an additional layer of clean fill to seal the actinolite or tremolite asbestos, soil, and rock. The depth of the fill should be sufficient to provide a factor of safety to ensure that exposure will not occur. The recommended depth is at least 6 in. of clean, compacted soil, as practiced by landfills. A cover planting (sodding, hydro-seeding) can be applied to ensure that the fill maintains the seal.

AIR-MONITORING RESULTS

The project monitoring reports submitted to the Fairfax APCD by contractors are the source of the data presented in this

paper. The reports include a daily description of work activities, weather conditions, and diagrams of the project that indicate the location of work activities and monitors. The air-monitoring results are listed by sample time, volume, and fibers/cm³ of air. Compliance with the significant ambient air concentration (SAAC) is determined by converting the raw data into a 24-hr average concentration. The equation presented in the Fairfax APCD CRD 2 for calculating the 24-hr average concentration is as follows:

$$\frac{(W \times S) + (2 \times MDC) + \{[24 \text{ Hr} - (W + 2 \text{ Hr})] \times BGC\}}{24 \text{ Hr}}$$

where

W = work day in hours,

S = sample results in fibers/cm³,

MDC = mean decay period concentration (concentration decays to background levels during the 2 hr following the end of the workday), and

BGC = background concentration is approximately 0.005 fibers/cm³.

$$MDC = \frac{\text{Start Concentration} + \text{End Concentration}}{2} = \frac{S + BGC}{2}$$

(NOTE: Because $2 \times MDC = 2 \times \frac{(S + 0.005)}{2} = S + 0.005 \approx S$
S may be substituted for $2 \times MDC$ as a simplification.)

Significant fiber levels above the PEL have been observed at construction sites. Fiber levels generated are dependent on work activities, control methodologies, weather conditions, individual worker performance, and mineralogical form and concentration of the actinolite and tremolite deposits encountered on the construction project. High-fiber air-monitoring levels in the actinolite or tremolite mineral deposits have even been encountered independent of visible asbestiform formations. The construction projects listed in Table 1 are within the orange soils group areas and have tested positive for the asbestos forms of actinolite and tremolite. The air monitoring results in Tables 2 through 5 are from these sites. Shown in these tables are areas in which standards have been exceeded and a potential to exceed the worker PEL and the public SAAC for many different work activities. They do not include the majority of the air-monitoring data that reflect compliance with the standards.

The bulk of the monitoring reports submitted show that the fugitive dust-control methods attenuate the exposure problem. When no fugitive dust-control methods were employed there have been dangerously high levels. During dry caisson drilling for asbestos soil Project 3, TEM analysis indicated an airborne asbestos concentration of 1.145 f/cm³ (Table 2, Project 3) near the property line. On the same project, a caisson inspector recorded a breathing zone concentration of 0.278 f/cm³ (Table 3, Project 3). Another project experimented using dry drilling methods with a tracked air drill to determine possible exposure for the employees. The fugitive dust was so dense that the experiment was stopped after 30 min. The air-monitoring results showed 0.3 f/cm³ (Table 2, Project 14).

TABLE 1 Natural Asbestos Soil Construction Projects

Project	Type of Project
1	Commercial Office High Rise Complex
2	Public Secondary School
3	Commercial Office High Rise Complex
4	Commercial Office High Rise Complex
5	Addition of Interstate Interchange Ramps
6	Expansion of Existing Fleet Garage
7	Residential Subdivision Project
8	Municipal 48 Inch Water Line Tunnel
9	Installation of Small Water Line
10	Residential Subdivision Project
11	Largest Residential Subdivision Project
12	Residential Subdivision Project
13	Small Shopping Center
14	Expansion of Existing Parking Decks.
15	Enlargement of Secondary Road Intersection
16	Widen an Existing Road to Four Lanes
17	Small Commercial Building
18	Religious Temple and Associated Buildings
19	Residential Neighborhood Utility Work
20	Addition of Interstate Interchange Ramps

TABLE 2 Air Monitoring Data from Caisson Drills, Air Drills, and Other Compressed Air-Driven Equipment.

Sample									
Proj	Date	Type	Meth	Volume Liters	Min.	Fibers / Cm ³	Notes	TWA	
1	7-6-87	BZ	TEM	54.6	39	0.14	DRY AIR DRILLING		
1	7-6-89	BZ	TEM	20.0	28	0.23	DRY AIR DRILLING		
3	7-15-88	AREA	TEM			1.145	CAISSON DRILL		
3	7-15-88	AREA	TEM			0.242	CAISSON DRILL		
3	9-29-88	AREA	PCM	1130	452	0.071	CAISSON DRILL		
3	9-29-88	AREA	PCM	723	289	0.45	INSIDE CAISSON		
3	10-17-88	AREA	PCM	160	64	0.164	CAISSON DRILL		
3	10-20-88	BZ	PCM	363	145	0.096	CAISSON DRILL		
3	10-21-88	AREA	PCM	815	326	0.096	CAISSON DRILL		
4	11-15-88	BZ	PCM		150	0.3	AIR DRILLER		.097
4	11-17-88	BZ	PCM		232	0.13	AIR DRILLER		.032
4	12-05-88	BZ	PCM		340	0.103	AIR DRILLER		.072
4	12-07-88	BZ	PCM		282	0.21	AIR DRILLER		.133
4	12-8-88	BZ	PCM		165	0.11	AIR DRILLER		.047
4	12-10-88	BZ	PCM		270	0.095	BLASTING		.075
5	7-10-89	BZ	PCM	211		0.127	AIR DRILLER		
6	7-17-89	BZ	PCM	1037	415	0.071	THIS PCM AND TEM		
6	7-17-89	BZ	TEM	1037	415	0.164	SAME SAMPLE-DRILLER		
6	10-18-89	BZ	PCM	350	140	0.068	HOE RAM		
6	10-18-89	BZ	PCM	338	135	0.070	HOE RAM		
7	10-25-89	BZ	PCM	252	240	0.126	AIR DRILLER		
7	10-27-89	BZ	PCM	246	240	0.544	AIR DRILLER		
7	10-28-89	BZ	PCM	240	240	0.075	AIR DRILLER		
7	11-2-89	BZ	PCM	240	240	0.296	AIR DRILLER		
7	11-14-89	BZ	PCM	708	354	0.355	AIR DRILLER		
7	11-14-89	BZ	PCM	69	30	0.092	" SAME MAN AS ABOVE		
7	11-15-89	BZ	PCM	445	445	0.279	AIR DRILLER		
7	11-29-89	BZ	PCM	638	425	0.097	AIR DRILLER		
7	11-29-89	BZ	PCM	60	30	0.682	DRY AIR DRILLING, WITH FABRIC FILTER		
7	11-30-89	BZ	PCM	540	360	0.142	AIR DRILLER		
7	11-30-89	BZ	PCM	60	30	0.045	AIR DRILLER		
7	1-19-90	BZ	PCM	473	315	0.092	AIR DRILLER		
7	2-1-90	BZ	PCM	585	390	0.122	AIR DRILLER		
7	2-6-90	BZ	PCM	570	380	0.184	AIR DRILLER		
7	2-8-90	BZ	PCM	488	325	0.106	AIR DRILLER		
7	2-12-90	BZ	PCM	60	30	0.094	AIR DRILLER		
7	2-21-90	BZ	PCM	435	290	0.111	AIR DRILLER		
7	3-19-90	BZ	PCM	581	287	0.129	AIR DRILLER		
9	7-10-89	BZ	PCM	63	35	0.11	AIR DRILLER		
16	10-4-90	BZ	PCM	453		0.40	HAND AIR DRILL		
16	10-4-90	BZ	PCM	247		0.10	HAND AIR DRILL		

NOTE: Proj.: Sample collected at this natural asbestos soil project. The number corresponds to that in Table 1. Type: BZ = employee breathing zone sample for OSHA compliance; AREA = sample collected near group of workers or perimeter of construction project. Meth.: TEM filter was analyzed by transmission electron microscopy, A and B protocols; PCM filter was analyzed by phase contrast microscopy according to NIOSH 7400 method. Fibers/cm³: Fibers per cubic centimeter of air as submitted in the air-monitoring report. TWA: Eight-hr time-weighted average for OSHA compliance.

OSHA action levels of 0.1 f/cm^3 have been exceeded despite implementation of proper dust controls. High risk for exposure to asbestos can be seen from the data in Table 2 for tracked air and caisson drillers. The sample data collected in Table 4 for earth-moving equipment show that they also produce OSHA action levels. The data in Table 3 for construction workers illustrate that even passive activities are at risk for

exposure. In one particular case, a surveyor inspecting storm drain structures was exposed to an average concentration of 0.73 f/cm^3 (Table 3, Project 16). One drain structure was actually located directly in a vein of actinolite asbestos. Because no other work was taking place during his inspection, the area had not been watered and was dry. Fortunately, the inspector was in the controlled area of this project and was

TABLE 3 Air-Monitoring Data for Construction Workers

Sample							Notes	TWA
Proj	Date	Type	Meth	Volume Liters	Min.	Fibers / cm^3		
1	8-29-87	BZ	PCM			0.079	GEO. INSPECTOR	
3	9-29-88	BZ	PCM	883	353	0.072	INSPECTOR	
3	9-30-88	BZ	PCM	1020	408	0.091	INSPECTOR	
3	10-7-88	BZ	PCM	213	85	0.278	INSPECTOR	
3	10-12-89	BZ	PCM	750	300	0.199	INSPECTOR	
3	10-14-89	BZ	PCM	100	40	0.260	INSPECTOR	.13
3	10-17-89	BZ	PCM	813	325	0.125	INSPECTOR	
4	5-18-89	BZ	PCM		128	0.12	LABORER	.06
4	5-20-89	BZ	PCM		282	0.10	LABORER	.06
4	7-7-89	BZ	PCM		100	0.72	LABORER	.17
4	7-12-89	BZ	PCM		275	0.15	" PUMPING H2O	.11
4	7-29-89	BZ	PCM		242	0.11	LABORER	.08
4	8-7-89	BZ	PCM		279	0.12	LABORER	.07
4	8-11-89	BZ	PCM		230	0.26	LABORER	.15
4	8-30-89	BZ	PCM		16	0.54	PIPE LAYER	.03
4	10-12-89	BZ	PCM		294	0.09	PIPE LAYER	.06
7	12-18-89	BZ	PCM	60	30	0.090	PIPE LAYER	
7	6-12-90	BZ	PCM	423	315	0.067	CABLE LAYER	
8	5-11-89	BZ	PCM	564	232	0.12	PIPE LAYER	.08
9	7-10-89	BZ	PCM			0.11	PIPE LAYER	
16	10-2-90	BZ	PCM	435		0.73	SURVEYOR	.27

NOTE: *Proj.*: Sample collected at this natural asbestos soil project. The number corresponds to that in Table 1. *Type*: BZ = employee breathing zone sample for OSHA compliance; *AREA* = sample collected near group of workers or perimeter of construction project. *Meth.*: TEM filter was analyzed by transmission electron microscopy, A and B protocols; PCM filter was analyzed by phase contrast microscopy according to NIOSH 7400 method. *Fibers/cm³*: Fibers per cubic centimeter of air as submitted in the air-monitoring report. *TWA*: Eight-hr time-weighted average for OSHA compliance.

TABLE 4 Air-Monitoring Data from Earth-Moving Equipment

Sample							Notes	TWA
Proj	Date	Type	Meth	Volume Liters	Min.	Fibers / cm^3		
4	1-24-89	BZ	PCM		190	0.14	LOADERS	.14
4	1-24-89	BZ	PCM		287	0.14	BULLDOZER	.14
4	8-2-89	BZ	PCM		272	0.11	TAMPER	.08
4	8-3-89	BZ	PCM		277	0.11	TAMPER	.10
4	8-9-89	BZ	PCM		415	0.11	ROLLER	.10
4	10-11-89	BZ	PCM		259	0.10	TAMPER	.05
4	8-31-89	BZ	PCM		168	0.09	TRUCK	.03
4	10-16-89	BZ	PCM		572	0.12	OPEN CAB	.10
5	6-26-89	AREA	PCM	214		0.12	TRUCK & LOADER	
5	6-26-89	BZ	PCM	90		0.05	TRUCKS	
5	6-21-89	AREA	PCM	561		0.04	LOADERS	
7	10-16-90	BZ	PCM	75	30	0.036	OPEN CAB BACKHOE	
15	7-5-90	AREA	PCM	365	146	0.075	TRUCK LOADING	

NOTE: *Proj.*: Sample collected at this natural asbestos soil project. The number corresponds to that in Table 1. *Type*: BZ = employee breathing zone sample for OSHA compliance; *AREA* = sample collected near group of workers or perimeter of construction project. *Meth.*: TEM filter was analyzed by transmission electron microscopy, A and B protocols; PCM filter was analyzed by phase contrast microscopy according to NIOSH 7400 method. *Fibers/cm³*: Fibers per cubic centimeter of air as submitted in the air-monitoring report. *TWA*: Eight-hr time-weighted average for OSHA compliance.

TABLE 5 Air-Monitoring Data from the Perimeter or Nonwork-Oriented Monitors

Sample									
Proj	Date	Type	Meth	Volume Liters	Min.	Fibers / Cm ³	Notes	TWA	
1	8-29-87	BZ	PCM			0.028	NEAR PERIMETER		
2	8-27-87	AREA	TEM			0.0195	NO WORK IN PROGRESS		
2	8-27-87	AREA	TEM			0.0165	NO WORK IN PROGRESS		
2	9-28-87	AREA	TEM			0.035	NO WORK IN PROGRESS		
3	1-20-89	AREA	PCM	315	126	0.144	WEST PERIMETER		
3	1-20-89	AREA	PCM	803	321	0.06	WEST PERIMETER		
4	4-25-89	BZ	PCM		163	0.05	NEAR PERIMETER .02		
5	6-27-89	AREA	PCM	1238		0.23	CLEARANCE		
6	6-5-89	AREA	PCM	1050	420	0.045	WEST END PERIMETER		
6	6-28-89	AREA	PCM	263	105	0.14	EAST OF WORK AREA		
6	6-28-89	AREA	PCM	900	360	0.046	FAR SOUTH WORK AREA		
6	7-10-89	AREA	PCM	1043	417	0.042	SOUTHERN PERIM AREA		
6	7-11-89	AREA	PCM	1075	430	0.042	SOUTHEAST PERIM AREA		
6	9-6-89	BZ	PCM	900	450	0.069	NEAR PERIMETER		
6	9-22-89	AREA	PCM	1060	424	0.060	DOWNWIND		
8	4-25-89	AREA	TEM & PCM	902	384	0.01	0.021 STRUCTURES/Cm ³		
8	4-25-89	AREA	TEM & PCM	1181	455	0.01	0.038 STRUCTURES/Cm ³		
8	4-28-89	AREA	PCM	132	56	0.04	NEAR DECON TRAILER		
9	7-10-89	AREA	PCM	59	58	0.09	DOWNWIND		
10	11-14-89	AREA	PCM			0.06	WEST EDGE		
10	11-14-89	AREA	PCM			0.04	WEST EDGE		
10	11-21-89	AREA	PCM			0.05	EAST EDGE		
15	7-5-90	AREA	PCM	363	145	0.058	PERIMETER		

NOTE: *Proj.*: Sample collected at this natural asbestos soil project. The number corresponds to that in Table 1. *Type*: BZ = employee breathing zone sample for OSHA compliance; AREA = sample collected near group of workers or perimeter of construction project. *Meth.*: TEM filter was analyzed by transmission electron microscopy, A and B protocols; PCM filter was analyzed by phase contrast microscopy according to NIOSH 7400 method. *Fibers/cm³*: Fibers per cubic centimeter of air as submitted in the air-monitoring report. *TWA*: Eight-hr time-weighted average for OSHA compliance.

wearing personal protective equipment. Normally, this passive work activity would not have been defined as a regulated area by the OSHA Asbestos Standard.

The perimeter of construction sites is monitored to protect the public from asbestos exposure. Perimeter sample results are obtained at the edge of the project boundary and can be more than 300 m or right next to the actual source of the fugitive emissions. In Table 5, high perimeter readings can be confirmed even when no work activities are reported on the site. In this particular case, Project 2, the project was highly contaminated with asbestos and the excavations were violent. Conversely, low readings are not unusual for very large construction projects with a substantial distance and buffer between the work and perimeter.

Because high asbestos levels like those previously mentioned are not easily predicted, it is necessary to be conservative with controls to ensure protection. Certainly, if good dust control and safety are practiced, protection for the public and employees can be achieved.

CONCLUSIONS

Naturally occurring asbestos represents a potential problem nationwide for anyone responsible for construction. Every

project involving or potentially involving deposits of asbestiform rock is regulated by OSHA Construction Industry Standard 29 CFR 1926.58. Because asbestos is a proven human carcinogen and NIOSH has concluded "there is no known threshold of exposure to asbestos below which there is no risk," it is imperative to protect everyone from asbestos exposure whether the project is temporary or long term. The presence of asbestos, confirmed by appropriate laboratory analysis, should be dealt with as a hazardous material regardless of its origin or the working circumstances. The asbestos regulations were promulgated to address the health risks associated with asbestos no matter where the exposure might be encountered. It is interesting that insurance companies have required more stringent state-of-the-art standards for naturally occurring asbestos construction projects. They recognize that existing regulations provide only the minimum protection and do not mitigate civil tort.

The air-monitoring data presented demonstrate the potential for asbestos exposure. Construction work can be successfully performed without exposure to employees if good dust controls are practiced. However, compliance with the regulations may require personal protective equipment and other special procedures. Also, dust control and limited access to the site are integral parts of complying with the regulations and reducing owner and contractor liabilities.

REFERENCES

1. Clifton, R. A. *What is Talc? Definitions for Asbestos and Other Health-Related Silicates*. ASTM STP 834 (Benjamin Levadie, ed.), ASTM, Philadelphia, Pa., 1984, pp. 158–174.
2. Johnson, L. K. *Survey of Mineral Deposits in Fairfax County Orange Soils Group*. Fairfax County Soil Science Office, Fairfax County, Va., 1987.
3. Johnson, L. K. *Soils of Fairfax County: General Ratings for Urban Development*. Fairfax County Soil Science Office, Fairfax County, Va., 1989, pp. 7, 11.
4. *Major Problem Soils Areas of Fairfax County Map*. Fairfax County Soil Science Office, Fairfax County, Va., 1979–1980.
5. Mossman, B. T., J. Bignon, et al. Asbestos: Scientific Developments and Implications for Public Policy. *Science*, Vol. 247, Jan. 19, 1990, pp. 294–301.
6. Lee, K. P. Lung Response to Particulates With Emphasis on Asbestos and other Fibrous Dusts. *CRC Critical Reviews in Toxicology*, Vol. 14, Issue 1, pp. 33–86.

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Asbestos Issues at Interstate 66 Road Improvements

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The Virginia Department of Transportation recently monitored the construction of road improvements along a 12.9-km (8-mi) section of Interstate 66 in Fairfax County, Virginia. Approximately 4 km (2.5 mi) of the road improvements were located in soils and rocks that contain naturally occurring asbestos (actinolite/tremolite). Precautions were exercised to protect the safety of the workers and the public from airborne particles. The presence of the asbestos added extra costs and time delays to the project. Part of the problem was the lack of clear language in the initial contract bid requests. It is best to acknowledge the presence of naturally occurring asbestos before a contract goes to bid.

The Virginia Department of Transportation (VDOT) has monitored the construction for road improvements to Interstate 66 in Fairfax County, Virginia. The improvements consisted of (a) a lane widening for high-occupancy vehicles (HOV), (b) adding a traffic lane in the median to replace a lane dropped at an exit (drop lane problem), and (c) installation of sound wall barriers. The entire project was approximately 12.9 km (8 mi) long, and the improvements were bid under different contracts. Approximately 4 km (2.5 mi) of the road improvements were located in soils and rocks that contain naturally occurring asbestos (actinolite/tremolite).

The purpose of this paper is to highlight the experience and lessons learned from the on-site VDOT inspectors and superintendents. The paper was prepared by interviewing Cher Kennedy, the project superintendent for a portion of the project, and her staff during July 1992.

The construction of these projects had to comply with Occupational Safety and Health Administration standards. The Virginia Division of Occupational Health, Department of Labor and Industry believes that there are two main issues regarding asbestos exposure. The first is health. The primary health consideration and source of entry into a body is through inhalation of airborne particles. Asbestos is known to produce two types of pulmonary cancer and interstitial lung diseases known as asbestosis. Employers may be liable for asbestos-related injuries many years after the conclusion of a project.

The second issue is the legal impact imposed by regulatory agencies to control asbestos exposure. The Virginia Division of Occupational Health, Department of Labor and Industry ruled in 1989 that employees exposed to natural asbestos are covered under the same standard as that for manufactured asbestos.

To satisfy the standards, contractors who encounter natural asbestos must, at the minimum, satisfy the following standards:

1. Monitor the employees for their potential exposure,
2. Establish a regulated area and control airborne particles

by using wet methods to eliminate dust,

3. Provide and ensure the use of respirators and protective clothing, and

4. Train the employees regarding the hazards of asbestos.

VDOT and the project contractor, Lane Construction of Meriden, Connecticut, had to comply with OSHA regulations. Lane also did not want any problems with the legal and liability issues concerning the naturally occurring asbestos. All workers were required to comply fully with OSHA regulations and were required to wear protective suits and respirators to reduce asbestos contamination as much as possible.

For VDOT, the main lesson learned from this project was not to use vague language in the contract documents. The first contract for this site was for the HOV lane widening. The bid documents issued by the Richmond VDOT office used language that said that naturally occurring asbestos "may" occur on site. This cautious language was used although VDOT had conducted test borings in the project area and knew that naturally occurring asbestos was present. As a result, the project experienced a \$1.2 million cost of extras caused by asbestos abatements and remediation. The initial bid for the project was \$9 million and with all the extras, including asbestos abatement, the project cost was approximately \$12.5 million. The additional cost caused by asbestos issues was approximately 9.6 percent of the total project costs.

The contract for the median lane widening contained specific language that naturally occurring asbestos was present. The cost of the lane widening project was approximately \$2 million, and the cost for the asbestos abatement was \$61,900. The cost for asbestos abatement and remediation was approximately 3.1 percent of the total project cost. Similar problems were encountered in both construction projects. On the basis of this comparison, it appears that the declaration of the presence of asbestos can reduce project costs.

When the asbestos problem was an extra, VDOT had to open a force account when monitoring this aspect of the project. They continually monitored the quantity of work done by the contractor, and paid him on a unit price basis. The state also had to train and equip their personnel and provide supervision of the asbestos work.

The asbestos work was not limited to one phase of any project, but extended throughout the project duration. Asbestos monitoring was required during excavation of road subgrades, storm sewer pipe excavation, and for the placement of signs. Sign placement occurred near the completion of the project. At any point where the earth materials were exposed, asbestos protection procedures were required. It is also important to note that the actual encountered asbestos was spotty within the asbestos-laden rock (Greenstone). The

actual location where asbestos material was found extended outside the areas shown on available maps.

Because of the presence of asbestos, a complicated series of contracts was made so that the project could continue. Lane Construction did not have and could not afford the required asbestos liability insurance. As a result, the abatement work was given to the Falcon Company, and Lane performed the construction work. The abatement work consisted of maintaining asbestos liability insurance and providing waste handling of used protective suits and contaminated wash water. Waste products were taken to registered asbestos dumps.

Lane also hired Hillmann Environmental Company of Virginia, Inc., to prepare a standard operating procedure (SOP) for the project and to provide the required inspection and monitoring services. The SOP, which was prepared to conform to OSHA standards, was prepared by Hillmann and submitted to VDOT for approval. As previously mentioned, the OSHA guidelines used for this project were primarily written for asbestos in building construction and not specifically for naturally occurring asbestos.

The SOP developed by Hillmann divides the construction project where asbestos was present into regulated and non-regulated areas. In areas not containing asbestos, the SOP is not applicable. Nonregulated areas were defined as areas where no earth moving or excavation occur. Regulated areas were defined as any area where earth moving occurs or where construction activity results in an elevated airborne fiber concentration.

The SOP showed the following items were required in regulated areas:

- Areas must be conspicuously marked;
- Warning signs must be posted for tremolite or actinolite, or both;
- A dust-suppression system to eliminate all visible emissions of dust and potential fiber release must be employed. Acceptable systems are (a) manual water misting using hoses, (b) sprinkler/wand systems, (c) water trucks, (d) amended water; and
- Sediment- and erosion-control systems must be installed to control runoff and prevent asbestos particles from leaving the site with overland flow.

Persons wanting to work within a regulated area were required to have passed a medical examination, to complete successfully a safety course that explained the hazards of asbestos and proper safety procedures, and to be fit-tested for respirators. To reduce delay time, a medical equipment van was brought to the site to give the physical examinations. Not all of Lane's employees passed the physical, and thus the available work force was reduced. A close-out physical was also required at the completion of the project.

Workers were required to log in and out of the regulated areas that were monitored by an inspector. Within the regulated area, they were required to wear OSHA-approved protective suits and respirators. Every time workers left a regulated area for breaks or to have meals, they were required to remove the protective gear and to take showers. The protective gear was not reusable and was kept for disposal on exiting the regulated area. The waste water from the showers was collected and later transported to an asbestos waste disposal site. Typical construction productivity rates were not

possible within regulated areas. The protective gear restricted workers' movements and reduced their efficiency. Excavation equipment operated at a slower pace to reduce the creation of dust. Additional time was also needed for decontamination and dust suppression and control measures.

All heavy equipment, vehicles, and small tools leaving the regulated area had to be decontaminated. Vehicles and heavy equipment were parked on a wash rack and regulated workers used shovels, spades, and other equipment to remove mud and other large debris from all surfaces. All interior and exterior surfaces and engine compartments were washed with a fire hose until visually clean and dust free. All cab areas and compartments were rinsed and wet wiped until visually clean. All accessible parts of the air systems of vehicles were cleaned. The air filters and other dry filter systems were replaced. This process was repeated each time the piece of equipment left the regulated area.

The decontamination process was lengthy and considerable down time was experienced. Each piece of equipment was inspected by the on-site asbestos consultant before its removal from the regulated area.

The contractor was required to monitor the asbestos exposure of the workers and the presence of airborne asbestos fibers at the project limits. This was done by having random employees in each worker classification wear a monitoring badge and by setting up air monitors at the perimeter of the site. The air monitors were spaced at approximately 76-m (250-ft) intervals. The badges and air monitors were checked several times per shift.

Workers did not experience significant exposure to naturally occurring asbestos in comparison with the prevailing standards. The highest recorded fiber content on any badge was 0.03 fibers/cm³. The permissible exposure level stated by OSHA was 0.2 fibers/cm³ for an 8-hr time-weighted average. The action level at which personnel should don personal protective gear was 0.1 fibers/cm³.

Grading and excavation in asbestos areas generated material containing asbestos that was not acceptable for use as compacted controlled fill or trench backfill. Such material was stored in on-site stockpiles located within the limits of asbestos. On completion of the stockpile, it was covered with at least 152 mm (6 in.) of clean, compacted, controlled fill that was seeded and mulched.

In-place soil and rock containing naturally occurring asbestos had to be sealed from the environment by nonasbestos earthen material. For pavement subgrades, soil containing asbestos was undercut 51 to 76 mm (2 to 3 in.). The undercut area was backfilled with VDOT No 21B coarse aggregate. In nonpavement areas, 152 mm (6 in.) of asbestos-free soil was used as cover.

In summary, the experience of the VDOT personnel at the I-66 project in Fairfax County was similar to that at other construction projects in the area. When naturally occurring asbestos was observed at the site, precautions were taken to protect the safety of the workers and the public. Projects in soil and rock containing naturally occurring asbestos add extra costs and time delays to the project. It is best to acknowledge the presence of naturally occurring asbestos before the contract goes to bid.

Development of Regulations Concerning Asbestos-Containing Aggregate for Road Surfacing

WILLIAM L. HUF AND EDWARD STUART III

In the late 1970s, the Pacific Southwest Region of the Forest Service, U.S. Department of Agriculture, embarked on a program to estimate the extent of public exposure to airborne asbestos particles from aggregate used for road surfacing and, if necessary, to restrict public exposure to this material. Asbestos emissions were measured during the operation of quarries producing asbestos-containing aggregate and the use of roads surfaced with asbestos-containing aggregate. On the basis of the results, abatement measures were adopted for aggregate-surfaced roads, native-surfaced roads, and off-highway-vehicle areas that contain asbestos. In 1991, the State of California enacted a regulation prohibiting the use of asbestos-containing serpentinite aggregate for road surfacing if the asbestos content should be greater than 5 percent. The Pacific Southwest Region of the Forest Service now follows the state regulation in its management of the use of asbestos-containing aggregate for road surfacing. The costs and benefits to the Pacific Southwest Region of this 5 percent limit are unknown, but probably small.

In the late 1970s the engineering staff of the Pacific Southwest Regional Office (Region 5) of the Forest Service, U.S. Department of Agriculture, embarked on a program to determine the potential for public exposure to airborne asbestos particles (longer than 5 micrometers) from aggregate surfacing on Forest Service roads. Region 5 lands are contained mostly within the boundaries of the State of California. Forest Service geologists determined that asbestos within Region 5 occurs principally in serpentinite and peridotite rock units, which are distributed primarily within the following geomorphic provinces of California: the Coast Ranges, Klamath Mountains, and the northern Sierra Nevada (1,2). Eight National Forests are located within these provinces. Occasionally, these forests used serpentinite and peridotite for aggregate road surfacing. In these forests were

1. Eight quarries mining serpentinite or peridotite;
2. An estimated 1660 km (1,030 mi) of road constructed in serpentinite or peridotite areas; and
3. An estimated 450 km (280 mi) of road surfaced with serpentinite or peridotite aggregate.

Additionally, these forests often purchased asbestos-containing aggregate from commercial quarries outside the forest boundaries.

To make a preliminary estimate of the extent of asbestos exposure to the public, the Regional Office engineering staff

studied rock-crushing and road-building operations using serpentinite. The study was done in 1979 in the Six Rivers National Forest, which is in the northern Coast Ranges Geomorphic Province of California (2). The results of the study, which used standard Occupational Safety and Health Administration (OSHA) air-sampling methods, were that exposures were within the OSHA permissible exposure level (PEL) in effect at that time (2 fibers/cc, time-weighted average over an 8-hr period) (3).

After a period of its own investigation, the Environmental Protection Agency (EPA) concluded in May 1981 that "Local, State, and Federal agencies responsible for road maintenance in the limited areas where asbestos emissions occur are in the best position to assess local conditions and implement the most appropriate control measures" (4).

AIRBORNE ASBESTOS EXPOSURE STUDY

Because of this decision by EPA not to pursue regulation of airborne asbestos emissions from aggregate-surfaced roads, Region 5 of the Forest Service decided to test worst-case public exposure along with worker exposure. Although no public PEL existed at that time (or exists now), it was decided that action would be taken to limit public exposure in locations where measured exposure approaches OSHA PELs for workers. Therefore, in 1981, the Regional Office retained the Radian Corporation of Salt Lake City, Utah, to measure asbestos levels in bulk rock samples from quarries and to measure airborne asbestos levels in operating quarries and along aggregate-surfaced roads in northern California (5). These quarries and roads were considered to be worst case with respect to expected levels of airborne asbestos generated, based on previous bulk sample testing and on the judgment of geologists working for the national forests.

Bulk rock samples were taken from the quarry sites, and airborne dust samples were taken both from the quarry sites and from roads surfaced with aggregate from these quarries. The airborne sampling was done using a procedure recommended by the National Institute of Occupational Safety and Health (NIOSH) (5). This procedure included pumping air for various periods of time at a rate of 2.0 liters/min through membrane filters with an 0.8-micrometer pore size. Pumps were placed in the cabs of earth-moving equipment at the quarries, beside roads surfaced with gravel from the quarries, and inside a vehicle traveling along these roads. Dust along the roads was generated in two ways: (a) vehicles repeatedly

passing a stationary sampling pump beside the road, and (b) a vehicle followed by a car with open windows, allowing air to be sampled by a pump inside the car.

STUDY RESULTS

Bulk samples contained <0.01 to 20 percent chrysotile asbestos, by volume. Air samples from quarry operations contained 0.09 to 0.10 fiber/cc (8-hr time-weighted average for fibers longer than 5 micrometers). Air samples from roads contained <0.01 fiber/cc to 0.27 fiber/cc. Therefore, all samples were within the 2-fiber/cc OSHA PEL. The airborne sample results obtained from the five quarries are shown in Tables 1 to 5.

FOREST SERVICE AIRBORNE ASBESTOS ABATEMENT MEASURES

Although at the time of the study the OSHA PEL was 2 fibers/cc, a stricter PEL of 0.1 fiber/cc had been recommended since 1976 by NIOSH and OSHA (3). In anticipation of the adoption of a stricter PEL [in 1986, a PEL of 0.2 fiber/cc was adopted by OSHA (3)], a Forest Service decision was made to abate public exposure to asbestos from aggregate-surfaced roads, native-surfaced roads, and off-highway-vehicle areas. Abatement measures included

1. Paving (typically with asphalt concrete);
2. Applying surface treatments, such as chip seals;
3. Covering with asbestos-free aggregate;

4. Applying dust palliatives, such as lignin sulfonate and magnesium chloride;
5. Controlling traffic; and
6. Restricting use during dry periods.

Many miles of existing aggregate-surfaced roads with the highest asbestos levels were paved with asphalt concrete. Forest Service-owned quarries discontinued the production of asbestos-containing aggregate for road surfacing. No restrictions were placed on the use of asbestos-containing riprap or on asbestos-containing aggregate for other than surfacing applications (for example, road base and aggregate in asphalt concrete). Public exposure to asbestos from aggregate-surfaced roads in Region 5 has decreased, although no airborne asbestos exposure data exist to determine the amount.

TABLE 1 Airborne Sample Results from Quarry 1

SAMPLE NUMBER	SAMPLING TIME	SAMPLE LOCATION	CONCENTRATION (FIBERS/CC)
01	0909-1144	INSIDE CAR	0.27
02	0955-1400	SIDE OF ROAD	<0.01
03	1026-1400	SIDE OF ROAD	<0.01
04	1058-1436	SIDE OF ROAD	0.03
05	1114-1447	SIDE OF ROAD	0.03
07	1127-1500	SIDE OF ROAD	0.01
08	1148-1513	SIDE OF ROAD	0.03
09	1335-1527	INSIDE CAR	0.12
10	1055-1202	INSIDE CAR	0.03

NOTE: The location of the quarry is 41°20' N, 122°31' W, Shasta-Trinity National Forest, Klamath Mountains Province. The samples were generated from vehicle use on a road with aggregate from Quarry #1. A bulk sample from the quarry contained 5-10 percent chrysotile asbestos.

TABLE 2 Airborne Sample Results from Quarry 2

SAMPLE NUMBER	SAMPLING TIME	SAMPLE LOCATION	CONCENTRATION (FIBERS/CC)
11	1147-1455	SIDE OF ROAD	<0.01
12	1125-1443	QUARRY	<0.01
13	1139-1449	QUARRY, STOCKPILE	<0.01

NOTE: The location of the quarry is 41°53' N, 124°04' W, Six Rivers National Forest, Klamath Mountains Province. The samples were generated from quarry operations and from vehicle use on a road with aggregate from that quarry. A bulk sample from the quarry contained 5-10 percent chrysotile asbestos.

TABLE 3 Airborne Sample Results from Quarry 3

SAMPLE NUMBER	SAMPLING TIME	SAMPLE LOCATION	CONCENTRATION (FIBERS/CC)
14	1020-1200	QUARRY, LOADER	0.09
15	1130-1420	SIDE OF ROAD	0.04
16	1037-1353	QUARRY, ROAD	0.03
17	1121-1411	SIDE OF ROAD	0.03
18	1300-1348	QUARRY, LOADER	0.10

NOTE: The location of the quarry is 41°45' N, 123°52' W, Six Rivers National Forest, Klamath Mountains Province. The samples were generated from quarry operations and from vehicle use on a road with aggregate from that quarry. A bulk sample from the quarry contained 1-2 percent chrysotile asbestos.

TABLE 4 Airborne Sample Results from Quarry 4

SAMPLE NUMBER	SAMPLING TIME	SAMPLE LOCATION	CONCENTRATION (FIBERS/CC)
19	1013-1216	QUARRY	0.04
20	1020-1218	QUARRY	0.11
21	1036-1327	QUARRY	0.06
22	1130-1503	SIDE OF ROAD	<0.01
24	1139-1516	SIDE OF ROAD	0.01
25	1218-1403	QUARRY	0.20
29	1320-1438	QUARRY	0.13
31	1405-1616	QUARRY	0.10

NOTE: The location of the quarry is 41°54' N, 123°02' W, Klamath National Forest, Klamath Mountains Province. The samples were generated from quarry operations and from vehicle use on a road with aggregate from that quarry. A bulk sample from the quarry contained 5-10 percent chrysotile asbestos.

TABLE 5 Airborne Sample Results from Quarry 5

SAMPLE NUMBER	SAMPLING TIME	SAMPLE LOCATION	CONCENTRATION (FIBERS/CC)
69	1110-1406	QUARRY	<0.01
71	1129-1415	SIDE OF ROAD	<0.01
81	1141-1428	SIDE OF ROAD	<0.01
82	1148-1435	SIDE OF ROAD	<0.01
83	1159-1437	SIDE OF ROAD	<0.01
84	1208-1440	SIDE OF ROAD	<0.01
85	1216-1445	SIDE OF ROAD	<0.01

NOTE: The location of the quarry is 40°03' N, 121°10' W, Plumas National Forest, Sierra Nevada Province. The samples were generated from quarry operations and from vehicle use on a road with aggregate from that quarry. A bulk sample from the quarry contained no asbestos.

STATE OF CALIFORNIA REGULATIONS

In 1989, the State of California Air Resources Board began the first phase of a three-phase plan to regulate asbestos generated from rock containing the mineral serpentine:

Phase 1: Regulation of asbestos-containing serpentinite rock used for aggregate in road surfacing;

Phase 2: Regulation of serpentinite quarries, mines and construction activities in areas of serpentinite rock, and off-road-vehicle activity in areas of serpentinite rock;

Phase 3: Further evaluation of existing roads surfaced with serpentinite aggregate to determine whether more stringent retroactive measures are needed (for example, paving).

Forest Service Region 5 engineers participated in hearings that were held for the Phase 1 part of the plan. These hearings resulted in the May 1990 State of California regulation entitled "Asbestos Airborne Toxic Control Measure, Asbestos-Containing Serpentine," which was signed into law in 1991 (6). This law prohibits the use of serpentinite aggregate surfacing for roads if it has an asbestos content greater than 5

percent. The law also provides for a test method for determining the asbestos content of aggregate sampled from quarry stockpiles or from roads. Phases 2 and 3 are planned for completion later.

Region 5 of the Forest Service follows the state law and now allows the use of serpentinite (or any other rock type) aggregate for road surfacing as long as the rock has an asbestos content of 5 percent or less.

CONCLUSIONS

The costs of adhering to the 5 percent limit are unknown, but probably low. Few rock sources in the Pacific Southwest Region contain asbestos percentages greater than 5 percent. Also, alternative sources with no asbestos, or less than 5 percent asbestos, are usually available for a modestly increased cost. Finally, in recent years, the number of miles of aggregate surfacing placed on National Forest roads has substantially decreased, because of causes such as reduced timber production.

The benefits of adhering to the 5 percent limit are also unknown, but probably low. On the basis of the Pacific Southwest Region's air sampling study discussed in this paper, public exposure to airborne asbestos particles from aggregate-surfaced roads has been historically quite low. Specifically, testing was on worst-case roads, generating the maximum exposure to dust for the conditions. Also, calculated exposures were based on the assumption that the road user travels continuously in a vehicle with open windows, directly behind another vehicle. Despite these conservative assumptions, only one test exceeded the permissible exposure limit, based on current OSHA PELs.

REFERENCES

1. *Geologic Atlas of California*. California Division of Mines and Geology, Department of Conservation, Resources Agency, Sacramento, Calif., 1958-1966.
2. Norris, R. M., and R. W. Webb. *Geology of California*. John Wiley and Sons, Inc., New York, N.Y., 1976.
3. *Federal Register*, Part II. Department of Labor, Occupational Safety and Health Administration, U.S. Department of Labor, 29 CFR Parts 1910 and 1926, June 20, 1986, pp. 22612-22615.
4. Serra, R. K., and M. A. Connor, Jr. *Assessment and Control of Chrysotile Asbestos Emissions from Unpaved Roads*. Office of Air Quality Planning and Standards, Environmental Protection Agency, Raleigh, N.C., EPA 450/3-81-006, 1981.
5. Simonson, A. V., J. M. Taylor, and R. Vandervort. *Asbestos Sampling and Analysis, USDA Forest Service*. Radian Corporation, Salt Lake City, Utah 84115, Oct. 26, 1981.
6. *Code of California Regulations*. Section 93106, Titles 17 and 26, CCR, May 22, 1990.

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Construction Considerations in Naturally Occurring Asbestos Areas: A Case Study

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A geotechnical investigation conducted to support construction of an office building in Fairfax County, Virginia revealed naturally occurring asbestos (actinolite and tremolite) at the project site. An asbestos-bearing rock, known as a greenstone/shist, occurs in the county. The six-story, 26 940-m² office building required blasting of rock and excavation. To protect public health, the Fairfax County Air Pollution Control Board became interested in monitoring the work site for asbestos emissions. In hopes of maximizing health protection and minimizing liability, the developer chose to develop an asbestos hazard abatement program. The Virginia Occupational Safety and Health Administration advised that regulations oriented toward the asbestos abatement industry should be applied on the site. SCS Engineers adapted requirements from the indoor abatement regulations for use at the outdoor construction site. A respiratory protection program was developed for the construction workers. Hazards were communicated, and workers were trained to use personal protective equipment and were fit-tested with respirators. Decontamination presented special challenges during the early stages of the effort due to lack of water, electricity, and heat. Medical examinations were performed to obtain information on worker health and fitness for respirator use. Where possible, engineered controls, consisting of dust control measures, were used. Air sampling was done to monitor airborne concentrations of asbestos in worker breathing zones and along site boundaries (to protect public health). Detailed records of site activities and air monitoring results were prepared and submitted to the Air Pollution Control Board on a weekly basis.

In 1988 SCS Engineers designed and implemented an asbestos hazard abatement program for construction of a six-story, 26 940 m² (290,000 ft²) office building and three-level garage on a 5.7-acre site in Fairfax County, Virginia, that is underlain by asbestos-bearing rocks. Approximately 2710 hectares (6,700 acres) of Fairfax County are potentially underlain by asbestos-bearing rock. Although hundreds of construction projects have been successfully completed in portions of Fairfax County underlain by naturally occurring asbestos, this project was among the first to address fully the health and safety considerations involved for workers and the public (1).

A preliminary site assessment and geotechnical investigation revealed the presence of naturally occurring asbestos in portions of this particular site, including areas scheduled for extensive excavation. The potential for a "dust hazard" during construction was identified at this phase of the project development. The Fairfax County Air Pollution Control Board became interested in monitoring the potential for off-site releases of airborne asbestos during construction in the mapped asbestos-bearing rock areas. In hopes of maximizing health protection and minimizing potential liability, the property owner

wanted to meet and exceed existing applicable regulations for mitigation of asbestos-related concerns on the site.

Geotechnical studies indicated the presence of naturally occurring asbestos in the decomposed rock at the site, commonly described as weathered greenstone, which occurred at depths from 0.6 to 4.3 m (2 to 14 ft). Solid rock was encountered in two rock core borings at depths of 3.0 and 5.8 m (10 and 19 ft). The preliminary site plans indicated that excavation for portions of the building, the garage, and the site utilities would involve some blasting of the solid rock and significant excavation in the decomposed asbestos-bearing rock.

In addition to excavation activities, the stockpiling of contaminated site soil materials formed a secondary potential for asbestos exposure by means of fugitive dust emissions. Excess soil stockpiles remained on site until the project approached completion, at which point the materials were hauled to an approved sanitary landfill. Because of the small size of the site, the materials frequently were transported and stockpiled on various portions of the site.

Several subcontracting firms were involved in the project; 13 subcontractors were directly involved in ground excavation activities. These trades were subject to the highest risk for potential asbestos exposure on the site. Additional secondary exposure risks for subcontractors not involved in excavation activities were posed by the site roads, which dried quickly and formed a source of fugitive dust emissions. The primary and secondary possibilities of exposure present on the site were considered in the development of the asbestos hazard abatement program.

PROGRAM DEVELOPMENT

Design of the health and safety program began with an extensive regulatory review. A variety of agencies were contacted to determine their jurisdiction with respect to naturally occurring asbestos. Agencies contacted included the Washington Occupational Health Association, the Virginia Occupational Safety and Health Administration (OSHA), the Mine Safety and Health Administration, the Environmental Protection Agency, the Virginia State Asbestos Coordinator, and the Virginia Department of Labor and Industry. Virginia OSHA advised that many of the health and safety policies contained in the regulations developed for the asbestos abatement industry should be applied on the site.

SCS was faced with meeting the intent of regulations designed for indoor asbestos abatement at an outdoor construction site. These existing regulations were not directly applicable for a variety of reasons. Strict application of the asbestos

policies conflicted with OSHA's safety standards for the construction industry. Maintenance of a regulated zone was difficult because of shifting wind patterns and the need for workers and equipment to traverse the site. The work was not conducted by experienced asbestos workers, thereby making the program execution a substantial challenge. From the perspective of the workers, construction was the primary focus and potential on-site asbestos risks were secondary.

Combining these constraints with regulatory considerations, SCS developed a three-pronged approach to the health and safety program, allowing room for continued review and improvements: to (a) protect worker and public health and safety, (b) meet applicable regulatory standards and guidelines, and (c) provide sufficient documentation and reporting to protect owner liability. SCS began the project with stringent personal protective equipment and other health and safety requirements, which were relaxed when deemed appropriate through continuing review of the air monitoring results. The program needed to apply during all phases of construction, accommodate a variety of trades, and manage between 1 and 70 site personnel at any given time.

The key elements and aspects of the SCS program included the following:

- A respiratory protection program was developed to establish a set of guidelines for respirator selection and use. The program was customized to address the needs of varied types of construction work.

- Worker training involved instructing workers on the hazards of asbestos and the need for protection. Worker training also included the fit of assigned respirators.

- Air sampling was done to monitor airborne concentrations of asbestos in worker breathing zones and along site boundaries (to protect public health).

- Engineering controls consisted of dust control measures. Wet methods were used during drilling, excavation, and transportation operations to limit the potential for generating airborne asbestos fibers. However, when the addition of water would interfere with the construction process (e.g., compaction), wet methods could not be employed.

- Personal protective equipment (PPE) also was used to limit worker exposure. PPE consisted of a half-face negative pressure respirator with high-efficiency particulate air filters, Tyvek or polypropylene coverall suits with hoods, and washable rubber boots, when appropriate.

- Decontamination was difficult initially because of lack of water, heat, and electricity on the site during project start-up. At that time, a series of wash basins were used outdoors. Eventually, a decontamination trailer with running water was established.

- Medical examinations were performed to obtain baseline information on worker health and to test worker fitness for respirator use.

- Detailed records were maintained on site conditions and activities through daily logs. Weekly project summaries were submitted to the Fairfax County Air Pollution Control Board.

AIR MONITORING RESULTS

On-site asbestos readings obtained usually were below the OSHA action level for personal breathing zones of 0.1 fibers

per cubic centimeter (f/cc) and below Fairfax County limit of 0.02 f/cc for off-site asbestos migration. However, certain activities and site conditions produced higher-than-average asbestos fiber releases.

Air monitoring results obtained during initial rock drilling and blasting operations indicated that potentially hazardous airborne asbestos concentrations could be released on the job site, warranting the continuation of the hazard abatement program. Breathing zone readings as high as 0.3 f/cc were obtained during dry drilling, which occurred on occasions when the water in the drill rig froze. When the operator was required to stand directly over the drill rig for an extended period of time, OSHA's action level of 0.1 f/cc frequently was exceeded. These results mandated the continuation of safe work practices, engineering controls, protective equipment, and monitoring on the job site.

Similarly, higher-than-average readings were obtained in other situations where engineering controls on dust generation could not be implemented. The OSHA action level was exceeded during final grading of the garage pad, where equipment operators obtained 8-hr time-weighted averages as high as 0.14 f/cc. The pad could not be kept wet, as the optimum moisture content for compaction would have been exceeded.

Work in semiconfined spaces, such as deep-site utility ditches and excavated building footings, also showed increased asbestos concentrations. Personal breathing zone readings approached the OSHA action level more frequently for workers in these portions of the site. The highest individual reading obtained in a semiconfined area was 0.54 f/cc. Backfilling operations using tampers to compact the soil also exceeded the OSHA action level occasionally. Once again, these asbestos dust levels were most likely due to construction restrictions on adding water to the backfill soils.

Ambient air readings at the site perimeter usually remained below the Fairfax County limit of 0.02 f/cc, even when site readings were elevated. Wind dispersal and the distance from site activities to the perimeter probably aided in keeping these readings low. Boundary readings that exceeded the 0.02 f/cc limit often could be attributed to other non-asbestos materials in use on the site. Similarly, high ambient air readings inside the building were found to contain no asbestos fibers, when analyzed using the more precise transmission electron microscope (TEM) methods.

RECOMMENDATIONS

Review of the procedures used on this project provides general recommendations concerning improved hazard mitigation during construction in naturally occurring asbestos:

1. A qualified asbestos consultant should be brought into the site-planning process as soon as the potential for an asbestos hazard is identified. Changes in the standard operating procedures can be made before the arrival of subcontractors to reduce the interference of the health and safety program with project progress. The contractor also can be informed of other site needs specific to the program, such as the requirements for on-site running water, heat, and electricity to provide for decontamination facilities.

2. All subcontractors and other employers on the site should be informed of the on-site asbestos hazard before or during

contracting procedures. In this way, compliance issues and awareness of the site requirements are made clear to all personnel who agree to work on the site. This procedure also will produce bid prices and work schedules that accurately reflect the additional site considerations, possibly serving to reduce contract conflicts.

3. The on-site chain of authority must be clear in order to provide adequate compliance with health and safety procedures. Enforcement and documentation form an integral part of a well-functioning hazard abatement program.

4. Personnel in charge of the site health and safety program should be actively involved in tracking project planning. When included in progress meetings at the site, the site safety personnel are able to predict adjustments that may become necessary to provide adequate worker and public health and safety.

CONCLUSION

The hazard abatement program focused on reducing worker and public asbestos exposure, meeting regulatory standards, and providing documentation of all aspects of the health and safety procedures. The project also created an opportunity to analyze the levels of exposure produced during construction in naturally occurring asbestos. This information is useful in analyzing the effectiveness of the site program, designing future programs, and aiding regulatory agencies in the development of effective and practical requirements to ensure a safe workplace.

Work at this particular site provided the Fairfax County Air Pollution Control Board with practical methods for reporting and documentation, allowing the development of regulations and guidelines that are now in effect throughout the county. Many of the procedures used at this job site have been recommended to other contractors working in naturally occurring asbestos as practical methods for reducing job hazards. Virginia OSHA currently is considering developing guidelines or regulations to address methods of providing a safe work environment during construction in naturally occurring asbestos. As regulatory interest in this type of job site continues to grow, it becomes increasingly important that accurate records are maintained to provide practical input to the regulatory guideline development process.

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REFERENCE

1. *Bridging to the 21st Century. Proc., 84th Annual Meeting and Exhibition*, Air and Waste Management Association, Vancouver, British Columbia, Canada, June 1991.

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