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Report No. FHWA-RD-75-17

PB242556



DEVELOPMENT AND EVALUATION OF CHEMICAL SOIL STABILIZERS

Earl B. Kinter



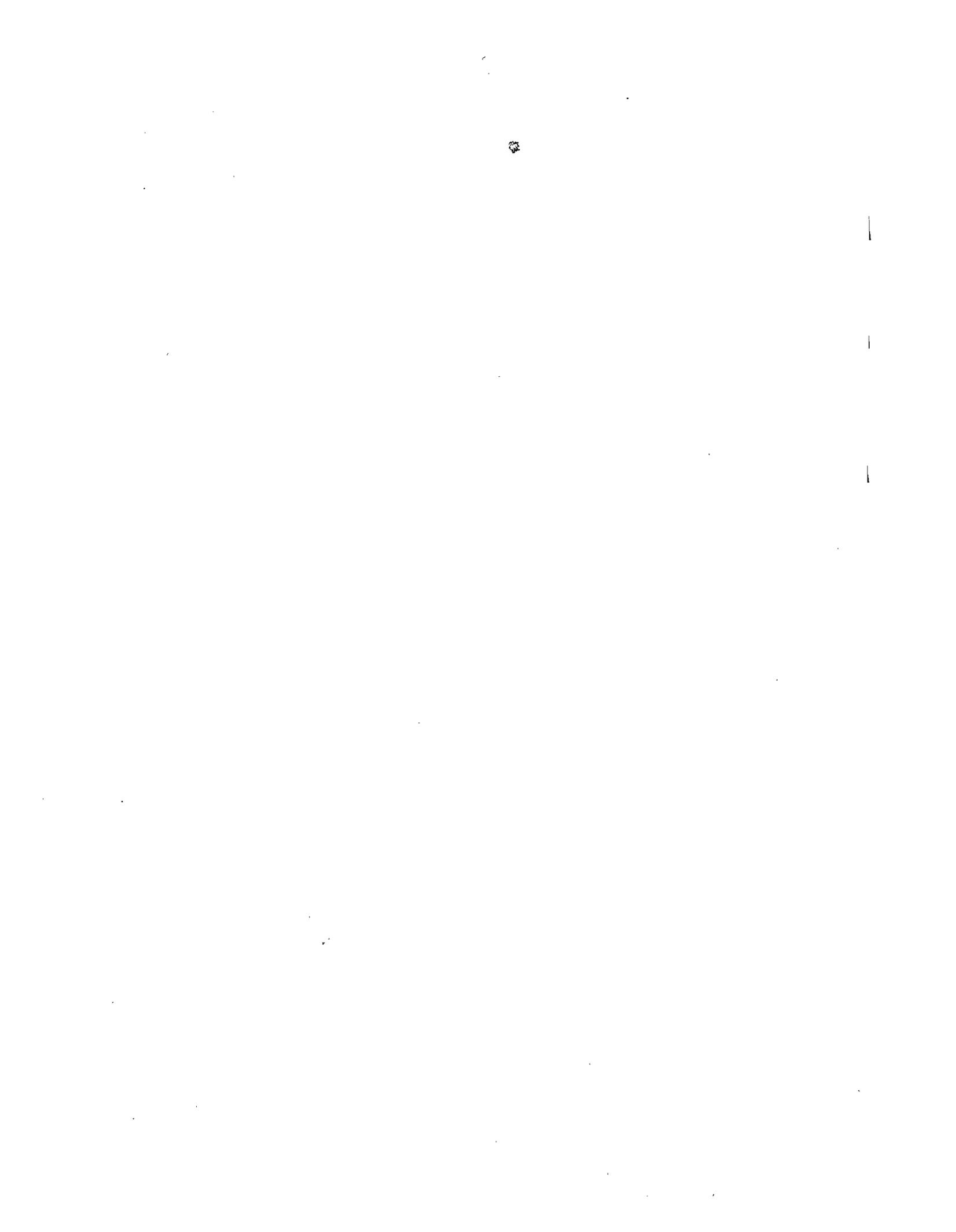
**March 1975
Final Report**

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Prepared for

**FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington D.C. 20590**



1. Report No. FHWA-RD-75-17	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development and Evaluation of Chemical Soil Stabilizers	5. Report Date March 1975	6. Performing Organization Code
	8. Performing Organization Report No.	
7. Author(s) Earl B. Kinter	10. Work Unit No. (TRAIS) FCP 24D2-002	
9. Performing Organization Name and Address Federal Highway Administration Offices of Research and Development Materials Division Washington, D. C. 20590	11. Contract or Grant No.	
	13. Type of Report and Period Covered Final Report	
12. Sponsoring Agency Name and Address U. S. Department of Transportation Federal Highway Administration Washington, D. C. 20590	14. Sponsoring Agency Code M-0204	
15. Supplementary Notes FHWA Project Manager: Donald G. Fohs (HRS-21)		
16. Abstract A study of chemical stabilization of soils began in 1954 with a program enlisting the aid of chemical industry in the search for effective chemicals. Nineteen firms signed a letter of agreement, and others cooperated on an informal basis. Federal participation consisted mainly of consultation, instruction, development of suitable laboratory evaluation test procedures, and review of test results furnished by cooperators. A number of chemicals, notably phosphoric acid, PDC, Terbec, lignins and quaternary amines, were proposed and evaluated in laboratory and field tests. Many others were given limited examination and laboratory testing. At about 1965, industry's interest shifted largely toward chemicals affecting compaction and moisture-density relationships of soils. Several proprietary compaction aids were evaluated by laboratory tests and one was the subject of field testing. A report on laboratory evaluation of two compaction aids has been prepared. No single chemical or combination of chemicals has been found acceptably effective or economical as a major soil stabilizer. However, further work with phosphoric acid and phosphates may make use of some of these substances possible. Prospects are promising for chemicals to improve moisture-density relationships and to supplement or enhance the effects of the major stabilizers, lime and portland cement.		
17. Key Words Soil stabilization; Soil treatment; Stabilization; Compaction aids; Soil densification; Soil testing.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21.



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1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is crucial for ensuring transparency and accountability in the organization's operations.

2. The second part of the document outlines the various methods and tools used to collect and analyze data. It highlights the need for consistent data collection procedures and the use of advanced analytical techniques to derive meaningful insights from the data.

3. The third part of the document focuses on the implementation of data-driven strategies. It discusses how the insights gained from data analysis can be used to inform decision-making and optimize organizational performance.

Conclusion

In conclusion, the document underscores the significance of data in modern business operations. It stresses that by leveraging data effectively, organizations can gain a competitive edge, improve efficiency, and make more informed decisions. The final part of the document provides a summary of the key points discussed and offers recommendations for future research and practice.

PREFACE

This report documents the results of a 20-year cooperative effort between the Federal Highway Administration (FHWA) and the chemical industry to develop and evaluate chemicals for soil stabilization. All evaluated substances were either ineffective or only marginally effective as principal or broad-scale soil stabilizers; however, some were suitable for improvement of local soils or for short-term correction of adverse soil conditions.

The test data obtained in the FHWA Soils Laboratory have been given to the respective cooperating companies, but no data are included in this research report. A request for the data for a specific product should be addressed to the specific company. Some materials and proprietary products were given only a limited evaluation, and some products may have been improved since the FHWA-sponsored evaluation was made.

Some of the proprietary products evaluated in this study appear in the "AASHTO-FHWA Special Product Evaluation List (SPEL)," August 1974. Other products evaluated in this study are not listed in the 1974 SPEL, hence this report may be useful as a supplement to SPEL.

Appreciation is expressed to the members of the chemical industry that participated in the cooperative study, as well as to the State and County highway departments that evaluated some of the products in field-scale experiments. Although the formal cooperative study has been completed, it is anticipated that the chemical industry will continue to develop chemical products aimed at soil stabilization, for use by the highway industry.

The draft of this report was prepared by Earl B. Kinter prior to his retirement in December 1973. His draft report was subsequently edited, primarily to include references to current research on compaction aids and industrial waste.

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INTRODUCTION

The term "soil stabilization" has been widely adopted to identify processes for improving inferior soils or substandard aggregates by blending with other soil or aggregate materials or by the addition of admixtures. Blending methods are commonly called mechanical stabilization. The use of admixtures is usually identified by the name of the additive, e.g., soil-cement stabilization. Since materials suitable for mechanical stabilization are often not available, dependence must be placed on the chemical admixtures. Portland cement and lime are the most widely used materials for stabilization. However, the great variety of soil materials and environmental conditions encountered in highway construction pose complex soil problems that are not fully met by the use of these principal stabilizers. A need existed, therefore, for additional effective stabilizing materials to either serve as principal stabilizers themselves, or as supplements or additives to lime and cement, so as to increase their effectiveness and make them more widely useful; hence the search for suitable and effective chemicals was initiated.

SCOPE AND GENERAL DESIGN OF STUDY

This study was directed to the investigation and development of specific chemical compounds, combinations of compounds and industrial products and wastes for soil treatment or stabilization. The work did not involve major studies of portland cement, lime or bitumens as such, though chemicals to supplement or enhance the effectiveness of any of these main stabilizers were included.

The study was designed to: (1) obtain major participation of the chemical industry by encouraging the use of their research and practical resources; (2) upon expression of interest from an individual or company, assist the industry representative by instruction and consultation, concerning the nature and properties of soils and the highway problems involved; (3) provide information on laboratory evaluation test methods; (4) upon receipt of proof that a chemical or product had promise as a stabilizer, conduct evaluation tests in the FHWA laboratory; and (5) aid in appropriate reporting, field-testing and implementation of findings. Industry's role was to provide the major initiative and investigation effort in the search for suitable new stabilizers; the Government's was to consult with and advise industry, further evaluate partly proven promising materials, and assist in implementing the practical use of materials shown to be effective.

GENERAL BACKGROUND

Prior to about the beginning of World War II, the treatment of soil materials with chemicals involved principally portland cement, calcium and sodium chlorides, lignins, tars and asphalts (1). Cement was used to provide strength and durability, as to a lesser extent were the bitumens; the chlorides and lignin were used to allay problems with dust, and to some extent, to control moisture during compaction of granular materials. The use of lime and lime-pozzolan mixtures, though dating back to the early Roman Empire, was localized and quite limited.

During World War II, the military needed rapid methods of improving soils in and adjacent to combat areas, hence considerable efforts were expended in investigating such chemicals as calcium acrylate, chrome-lignin, aniline-furfural, asphaltic mixtures and specific chemical compounds. Investigations were also begun by the Federal Highway Administration (FHWA), the Civil Aeronautics Administration, and by universities, industry, and highway departments, with highway and airport usage in mind. FHWA investigations up to 1953 dealt with a considerable number of chemicals and generated several reports, only some of which were published. The studies are listed in Appendix A, with brief annotations regarding studies for which no report was published.

COOPERATIVE EFFORT WITH CHEMICAL INDUSTRY

By 1954, both highway officials and chemical companies generally had become much interested in the possibilities of chemicals for soil treatment. This interest was influenced by the great expansion of highway construction and an awareness of the economic potential involved in treating the tremendous volumes of soil materials that would be handled. Under the leadership of Frank R. Olmstead, Federal Highway Administration, a program enlisting the aid of chemical industry was begun in 1954, by direct approach to some companies, and also using magazine and newspaper articles for publicity to arouse the interest of others (2). This generated a considerable activity in the form of both personal consultations and discussions, as well as correspondence.

Letters of Agreement

A letter of agreement (Appendix B) stated the responsibilities of the cooperating company and the Federal Highway Administration in the program for development and evaluation of chemical soil stabilizers. The agreement provided assurance to industry that the fruits of their expenditures in this effort would be safeguarded, and simultaneously protected the Federal Highway Administration against a flood of untested products that would reduce it to a testing agency for industry.

Within about two years of the initiation of the program, 16 letters of agreement had been signed and three others were signed in later years. The 19 companies and organizations are listed below.

American Cyanamid Co.
Armour Industrial Chemical Co.
Dow Chemical Co.
E. I. Du Pont de Nemours Co., Inc.
Food Machinery & Chemical Corp. (Westvaco Co.)
General Aniline & Film Corp.
General Electric Co.
General Mills, Inc.
Koppers Co.
Monsanto Chemical Co.
Morton Salt Co.
Pillsbury Co.
Products Development Co.
Rayonier, Inc.
Stauffer Chemical Co.
Sulphite Pulp Manufacturers Assn.
Tennessee Corp.
Tropical Agricultural Research Corp.
Union Carbide Co.

Several companies sent scientists or technicians to the FHWA Soils Laboratory for instruction in soil stabilization generally and evaluation tests and procedures particularly. These instruction visits were usually for one week; in some cases the company representatives returned later for further brief periods of consultation and instruction. Some of the signing companies, however, were much less active, and provided little evidence showing that their interest had continued.

Companies Cooperating without Letter of Agreement

In addition to those companies and organizations operating under letters of agreement, many were involved in the program without this formality; these are listed in Table 1. For convenience in cross checking, specific stabilizer names are given in some cases along with the company name. Participation ranged from a single visit by a representative or an inquiry by mail and a brief exchange of correspondence, to lengthy discussions and correspondence extending over considerable periods of time -- in some cases, years. The greatest activity was early in the study, shortly after the 1954 request for industry's assistance, but inquiries were received all through the intervening period.

Table 1. Inquiring and cooperating companies and organizations not having a letter of agreement

Allied Chemical and Dye Corp.
American Basic Chemicals, Inc. (Basic (R))
American Can Co. (Dust palliative, soil stabilizer, lignins)
Archer-Daniels-Midland Co.
Borden Inc. (Geoseal)
Bower, Inc. (Earth-Pak)
Business Development International (Fujibeton)
Celanese Corp. of America
Central Chemical Co. (SA-1, ClaPak, ClaSet, KelPak)
Compaction Engineering Co. (SC-100)
Construction Chemicals, Inc.
Crosby Chemicals, Inc.
Davison Chemical Corp.
Deutsche Terrabind - Erdstabilisierings - GMBH
Dow-Corning Corp.
Durez Plastics and Chemicals, Inc. (Hooker Electrochemical Co.)
Esso Research and Engineering Co.
Golden Bear Oil Co.
B. F. Goodrich Chemical Co.
Gra-Kote (Compact)
Herrick L. Johnson, Inc.
Humphrey Corp.
Imperial Chemical Industries Ltd.
International Minerals and Chemicals Corp.
Larutan Corp. (Paczyme, Aquatain)
Midwest Research Institute
Nacco Etablissement (Soil Consolid-Road Packer)
National Aluminate Corp.
National Lime Assn.
Pennsalt Chemicals Corp.
Quaker Oats Co. (furfural)
Riverton Lime and Stone Co., Inc. (hydraulic lime)
Rohm and Haas Co. (calcium acrylate)
Shell Chemical Corp.
Sodium Silicate Mfgr's. Inst.
Soil-Seal Corp. (Soil-Seal)
Socony Mobil Oil Co.
Standard Oil Company of Indiana
Sunoco Products Co.
Terra-Perma, Inc. (Kompak and Permaste)
R. T. Vanderbilt Co., Inc.
Velsicol Chemical Corp.
Victor Chemical Works (phosphates)
Zel Chemical Co. (Road Packer, Reynolds Road Packer)

Major Participation

Many of the companies responding to the request for cooperation ultimately expended considerable effort in attempting to develop effective chemicals or in testing various of their products. These activities also required a considerable expenditure of time by Federal employees. The major participants are listed below; part A lists companies and organizations interested in conventional stabilization, and part B lists companies dealing with aids to soil compaction.

A. Stabilizing agents

American Cyanamid Co. (AM-9 chemical grout, Cyanoloc 62 and others)
Armour Industrial Chemical Co. (Arquad 2HT, amines, chemical for asphalt emulsions)
Dow Chemical Co. (Terbec, calcium chloride)
General Mills, Inc. (Aliquat H-226, other amines)
Monsanto Chemical Co. (phosphoric acid)
Products Development Co. (PDC)
Rayonier, Inc. (lignin and cellulose derivatives)
Riverton Lime and Stone Co. (hydraulic lime)
The Salt Institute (sodium chloride)
Tennessee Corp. (phosphoric acid)

B. Compaction aids

Gerald C. Bower, Inc. (Earth-Pak)
Central Chemical Co. (SA-1 and others)
Construction Chemicals, Inc. (Terrafirmer)
Gra-Kote Co. (Compact)
Larutan Corp. (Paczyme and others)
Terra-Perma, Inc. (Kompak and Permasteer)
Zel Chemical Co. (Road Packer)

Chemicals Considered for Soil Treatment

During the course of the cooperative study, attention was given, in varying degrees, to about 50 chemicals and proprietary products. These materials are listed in Appendix C. With a few exceptions, such as phosphoric acid and salt, the listed items are mixtures of various chemicals rather than specific compounds; most of the items have trade names, some are waste products, and many are proprietary.

DEVELOPMENT OF EVALUATION TEST PROCEDURES

In order to determine the effectiveness of proposed stabilizers, test procedures to measure changes in soil properties were required. Soil properties of greatest concern were plasticity, density, strength, and volume changes resulting from changes in soil moisture content. As such properties had long been of primary importance in highway considerations, soils engineers had developed a number of appropriate laboratory test methods for use with raw soils. For particular use in evaluating stabilizers, some of the standard methods were adopted unchanged, others were modified as required to accommodate the change from raw to stabilized soil. The laboratory procedures for evaluating chemical soil stabilizers in the study are given in Appendix D. This version is the latest in a series of revisions that were required to reflect improvements in methods and techniques.

Normally, as part of discussions with a company that had expressed considerable interest in a cooperative effort, or upon signature of the letter of agreement, a copy of the test procedures was supplied to the company. In most cases, equipment and procedures were briefly demonstrated for the company's technical representative; in a few cases, the representative was trained in the FHWA Soils Laboratory. Samples of soils for use in the evaluation tests were sometimes furnished to the cooperator early in the study, but this procedure was replaced by one of providing advice as to appropriate types and source locations of soils for testing.

The evaluation procedures were designed to measure changes in "conventional" soil properties and behavior, as noted above. However, especially in the case of compaction aids, it was necessary, in some cases, to further revise the procedures to provide somewhat unusual test conditions required by unusual specifications of producers -- for example, to provide partial drying back of treated soil, or to compact test specimens at other than standard compactive efforts. These revisions are not included in the procedures given in Appendix D.

MAJOR DEVELOPMENT AND EVALUATION EFFORTS

The earlier search for effective chemicals, conducted by various agencies and individuals, involved then existing products that were originally produced for other uses (artificial resins, asphaltic emulsions, tars) as well as numerous specific chemical compounds, seemingly selected "from the shelf," for little apparent reason other than availability. Thus, at the outset of the cooperative phase of study, much of the preliminary screening process had been completed,

and it was possible to view somewhat more realistically the difficulties and the likelihood of developing effective stabilizers. Findings of the earlier work, coupled with the requirement that a given chemical must make a favorable showing in the evaluation tests, effectively reduced the time and effort required for most of the items listed in Appendix C. However, with some of the materials, as described below, major efforts in testing, consultation and correspondence were involved.

Quaternary Amines

Quaternary amines are widely used by-products of the meat packing industry and form a large group of organic compounds of ammonia. Because of their cationic nature, they react readily with soil clay minerals, producing a strong flocculation and a considerable degree of water repellance. Despite much work, however, by Armour Industrial Chemical Company, General Mills, Inc., and others, the amines were not found to be significantly effective for treating highway soils.

PDC

This product of the Product Development Company is a mixture of portland cement, hydrated lime and casein. During its development and evaluation, the proportions of the ingredients were repeatedly adjusted by the company, and various types of milk casein and soybean casein were tried. The company's test results showed PDC to be an effective stabilizer for clay soils. However, FHWA tests did not show PDC to be significantly more effective than the same cement-lime mixture without casein. A number of successful field sections using this product were constructed on secondary roads through the company's efforts, but the additional cost of the seemingly unnecessary ingredient, casein, could not be economically justified, hence no practical use of the product has resulted.

Terbec

Dow Chemical Company developed a rapid, inexpensive test for evaluating their products and experimental chemicals as stabilizers, and applied the test to thousands of compounds. Although they have not revealed the details of the test, the test results or the identity of the tested chemicals, they advanced Terbec (chemical name -- 4-tert-butylpyrocatechol) for further consideration (3). In FHWA tests, Terbec was an effective waterproofer, but it did not permanently strengthen or otherwise improve clayey soils, and full attainment of its limited effects required some drying back of originally moist soil mixtures. In cooperation with the Minnesota Department of Highways, Iowa State University, the Iowa State Highway Commission, and various county highway departments, the company

installed 25 test projects in six States. The limited reports provided FHWA indicated that some sections having Terbec-treated soil as base or subbase gave better performance than the control sections having standard construction; however, in other experimental projects the performance of Terbec-treated sections was either inferior or no better than sections having standard design. Initial claims that Terbec provided resistance to frost action were not substantiated by later observations.

Lignin Liquors and Lignin and Cellulose Compounds

The sulfite process in the paper industry, in extracting lignin from wood, produces vast quantities of a liquor containing about 10 percent lignin and 90 percent water. Even before the present emphasis on controlling pollution, paper companies were attempting to profit from this by-product; more recently they have been attempting to dispose of the liquor to avoid water pollution. Early efforts were directed to the use of the liquors in palliating dust on unpaved roads, and to reduce the permeability and frost action of the natural soil; hence, they had a widespread, if modest, success (1, 4). Hauling costs of dilute liquor and the expense of reducing the water content of the liquor to 50 percent or less, however, severely restricted usage. Attempts to use the concentrated liquors in conventional stabilization have not been very successful. Development of the chrome-lignin process was at first promising, but the costs were excessive and effectiveness in producing strength and water resistance depended on at least a partial drying back of treated soil, an impractical requirement in field use.

Rayonier, Inc., exerted major efforts in the early work on lignin liquors and renewed their efforts more recently with cellulose and lignin compounds. The company submitted one material they considered to have merit for waterproofing soils. FHWA tests indicated that the material slightly increased the strength of soils, but that its overall effect on soil improvement was insufficient to warrant field evaluation.

In recent research with lignin liquor, Iowa State University used aluminum sulfate and lime additives to lignosulfonates in laboratory and field studies of dust palliatives (4). Field trials indicated that the additives did not significantly increase the effectiveness of the lignosulfonate as a dust palliative; however, the lime additive reduced the loss of aggregate caused by traffic abrasion.

Phosphoric Acid

Monsanto Chemical Company found that phosphoric acid reacted with soils to increase their strength and water resistance. Tennessee

Corporation also did considerable experimentation with phosphoric acid. Field test sections were constructed in Georgia and Missouri. Although the acid was fairly effective with soils in eastern United States, the cost was too high for successful competition with lime and cement, and the treated soil was difficult to compact. Test results in the FHWA Soils Laboratory were encouraging. However, a severe limitation was found with calcareous soils, the acid being consumed by the soil without producing adequate strength. Although the acid could be treated to eliminate the corrosion of road building equipment, its probable effects on workmen discouraged further attempts at its use.

Asphalt Emulsions

Aside from cement and lime, asphalt has perhaps been the most logical candidate for experimentation in stabilizing soil, considering its low cost, general availability, long time use for mixing with aggregates for producing surface courses, and its recognized water repellent nature. Difficulties with mixing asphalt cements with soil and with solvent retention of cutbacks -- as well as the relatively ineffectiveness of both in producing strength that is retained on exposure of the soil to moisture -- led to experiments with the emulsion form. The use of asphalt emulsions was only partly successful, due to incompleteness of waterproofing, and the fact that with moist or wet soils, construction difficulties arose because of the additional water contained in the added emulsion. Subsequent to consultation with representatives of Armour Industrial Chemical Company, cationic emulsions were developed which seemed to be reasonably effective with soils of low plasticity. The emulsion "breaks" properly, water is expelled by rolling operations, and apparently adequate strength is quickly developed. The company cooperated with States and Counties in field experiments to prove the effectiveness of the emulsion. Company representatives indicated that the improved effectiveness results from additives they have developed.

Special Limes

Hydraulic lime differs from "normal" high-calcium hydrated lime in that it is produced by burning impure limestones (i.e., containing clay and silica). It thus contains modest contents of portland cement-like material in addition to the somewhat lowered content of calcium hydroxide. Because of this cement content, it is an effective stabilizer, but is not as effective as either portland cement for those soils normally reacting with cement or high-grade lime for those reacting with lime. It will, however, probably receive greater attention in the future, as stabilization practices using combinations of cement and lime become more widespread, and in areas where high-grade limestone is not available for lime production.

Waste lime from acetylene plants is normally a high-grade calcitic lime in paste form and is available in very great quantities. Experiments have shown it to be about as effective as the equivalent quantity of dry lime, and it thus can be utilized where soil-lime stabilization is practiced. Handling of a lime paste -- as opposed to bagged dry lime -- is a considerable problem, and hauling costs, because of the water content, are unfavorable. Greater future use of this form of lime may depend on the incentive created by the necessity to dispose of the large stockpiles of this waste material.

Industrial Wastes

Industry in general has been attempting to dispose of waste products for many years, usually preferring to consider them as by-products and potentially profitable. As indicated above, lignin wastes -- except for dust control -- have proven to have limited use for soil treatment. Flyash was given considerable attention in early experimentation, and its use in combination with lime for soil stabilization is increasing. During the course of the study a number of other waste materials have been brought forward -- for example, red muds from the aluminum industry -- but none has been found to be both practical and effective.

Because of the public's need to dispose of or utilize industrial, mineral and domestic wastes, FHWA initiated a research project, "Use of Waste as Material for Highways," in 1972. The project includes a study on the use of waste sulfate for remedial treatment of soils, which is scheduled to be completed in 1976.

Compaction Aids

In the early stages of the study, particularly with respect to the activities of the larger companies, interest centered largely on the stabilization aspect of soil treatment with chemicals. More recently the emphasis has shifted to the potential use of chemicals to improve moisture-density relationships -- i.e., reduce the effort, lower the water requirement, and attain a higher density. For example, Road Packer, Earth-Pak and Terra Firmer, though first proposed as stabilizers, were claimed to attain this end largely by providing higher soil density. A considerable number of companies are promoting their proprietary compaction aids.

Road Packer was tested in the FHWA Soils Laboratory to provide information requested by FHWA field offices, and was found to be ineffective as a stabilizer. Its composition and source are not known, but it has a high content of sulfuric acid (along with sulfonated hydrocarbons), such as would be expected in a waste product of the detergent industry.

Paczyme, among several other proprietary compaction aids, was widely promoted in 1968-72. Tests in the FHWA Soils Laboratory did not substantiate company claims regarding its effectiveness as an aid to compaction. FHWA personnel gave technical guidance to Virginia in a State-funded field evaluation of Paczyme. An HP&R study of Paczyme was also made in North Carolina. These field tests failed to show beneficial effects of Paczyme on density or compactive effort.

Additional data on the laboratory performance of Paczyme and Road Packer were obtained in the FHWA Soils Laboratory, and a report of the findings was prepared (5).

Various other products tested in the FHWA Soils Laboratory seemed to be wetting agent and surfactant formulations. They showed some effects on soil compaction, but their function and possible application is unclear. The potential for chemical treatment to improve the compactibility of soils was so great that FHWA initiated a contract research study in 1973, to make laboratory and field evaluations of chemical compaction aids and proprietary products marketed as compaction aids. The study is scheduled to be completed in 1976.

CONCLUSIONS

The following conclusions are based on the very considerable search made by a large number of researchers engaged in this cooperative study, as well as by other researchers acting independently or under sponsorship of other agencies:

1. No single chemical or combination of chemicals has been found acceptably effective as a major soil stabilizer. It is deemed unlikely that an effective, economical principal soil stabilizer will be found. However, further work with phosphoric acid and phosphates may make use of some of these substances possible.
2. Prospects are promising for chemicals to: (a) improve moisture-density relationships of soils, i.e., reduce the energy required for compaction and reduce the water requirement, and (b) supplement or enhance the effects of the major stabilizers, lime and portland cement.
3. Recent developments with asphaltic emulsions suggest that their effectiveness and practical use for soil stabilization may be substantially increased by the use of additives.
4. Locally, waste lime that does not meet the normal specifications for high-grade lime for other construction may be suitable for soil stabilization.

CRITIQUE OF STUDY AND PRESENT OUTLOOK

In the early attempts to modify soil properties with chemicals, very little useful information was available concerning the basic nature and properties of the various constituents and fractions of soil materials. Engineering soil tests dealt mostly with strength properties and empirical considerations of plasticity and other soil-water relationships. Local problem soils utilized for testing the effects of chemical treatment were of uncertain composition, and could not be regarded as representative of any broad range of natural soils. Similarly, the selection of chemicals for experimentation was based on factors such as general familiarity, ready availability or a company's request for consideration of their product, than on firmly based technological reasons.

The 1954 cooperative program continued this method of operation, but in a somewhat more organized fashion and on a larger scale. The voluntary aid of the chemical industry was effectively harnessed, and by utilization of its research talent and profit motivation, the inevitable pressure on both Federal and State highway organizations for extensive testing and evaluation was considerably reduced.

Some of the research conducted by industry -- as well as some conducted independently by others -- was soundly based on consideration of the nature and properties of soils and the physiochemical problems involved in their remedial treatment. Much of the work was not so based, however, and few of the products listed in Appendix C had any realistic potential as soil stabilizers. On the other hand, however, the study was eminently successful in directing industry's efforts toward development and testing of their own products, properly reducing the Federal effort largely to technical consultation and instruction, and thus mitigating the natural efforts of industry to obtain free testing and evaluation services.

It has long been apparent that the general, Edisonian approach involving random testing of existing specific chemicals (both organic and inorganic), of waste products, and of industrial products originated for other purposes, is unlikely to reveal new, effective and competitive major soil stabilizers. Indeed, the volume of completed testing and the great number of low-cost materials that have been evaluated, along with the present greater knowledge of the physiochemical makeup of soils, suggest that development of such a stabilizer is unlikely in any case. The approach used in this study in recent years reflects these conclusions. On the other hand, it is also clear that treatment with limited amounts of chemicals can significantly affect some properties of soils in ways that may have considerable economic impact -- for example, in moisture-density relationships such as lowering moisture and compactive effort

requirements, increasing density, reducing frost action, and controlling volume changes. Current and planned research is concentrating on these aspects. Similarly, it is known that chemical additives can increase the usefulness and effectiveness (and reduce the cost) of the major stabilizers, cement and lime. Research studies will be developed along these lines. Current research also involves the development of information on the effectiveness of calcitic and dolomitic limes in treating major U.S. soil types, and recommendations on the selection of the proper lime type for specific soils or soil areas.

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APPENDIX A

Research Conducted by the Federal Highway Administration on Use of Chemicals for Soil Stabilization, 1939-1953

1. Studies of Water Retentive Chemicals as Admixtures with Nonplastic Road-Building Materials, by E. A. Willis and C. A. Carpenter, PUBLIC ROADS, Vol. 20, No. 9, 1939.
2. Study of Effect of Hydration of Cement on Density, Absorption and Punching Shear Stability, by P. Rapp, unpublished (work done in 1939).
3. Chemical Treatment of Chert Gravel for Use in Base Course Construction, by E. A. Willis and P. C. Smith, PUBLIC ROADS, Vol. 21, No. 4, 1940.
4. Study of the Effect of the Chemical Properties of Soil Fines on the Performance of Soil-Aggregate Mixtures, by P. Rapp and J. Mizroch, unpublished (work done in 1940). Correlated base exchange and chemical analysis of soil colloids with service behavior of roads located in several States.
5. Lignin Binder Used in Test Sections Subjected to Accelerated Traffic, by E. A. Willis and R. A. Lindberg, PUBLIC ROADS, Vol. 22, No. 8, 1941.
6. Laboratory Tests and Research on the Addition of Various Grades of Tar to Clay Soil, by P. Rapp and S. Rixse. Data compiled in 1941-42 on compaction, Rhodes stability, Barrett test and triaxial compression, but no report made.
7. Research on the Use of Stabinol in Soil Stabilization, by J. A. Kelley, 1945 (unpublished). Extensive laboratory tests on strength, absorption, and volume change for various types of soils and percentages of admixtures.
8. A Study of Tung and Soybean Oils as Admixtures to Improve Soils for Base Course Construction, 1946, unpublished. Work performed by Chinese engineering students in FHWA Lab.
9. A Study of the Use of Various Chemical Admixtures on Five Different Types of Soils, by W. K. Taylor, 1948-49. This was a cooperative research project with the U. S. Corps of Engineers, Ft. Belvoir, Va. Periodic reports of test data furnished informally to military at Ft. Belvoir; no official report published. Studies involved the following chemicals: Dustrol, Triton X-45, Silicone 500, and Aggrecoat.

10. Progress Report on Laboratory Investigation of Testing Procedures Suitable for Determining Properties of Stabilized Soil-Bituminous Mixtures, by J. Kelley, unpublished. Work in 1950-51 provided test data for several methods of evaluating soil-bituminous mixtures. Since there were no field tests to evaluate field performance, no recommended test method for mixture evaluation was made. It was suggested that a field test be initiated to provide performance data for correlation with laboratory evaluation of the soil-bituminous mixtures.
11. Laboratory Tests and Research on Physical Properties of Soils with Admixtures of Lime, by J. Kelley, unpublished. Exploratory study in 1950.
12. Exploratory Study of the Use of Additions of Hydrated Lime and Portland Cement as a Soil Modifier, by J. A. Kelley, 1950, unpublished. Changes in liquid limit and plasticity index, curing, volume change effects were investigated.
13. Exploratory Study on Lime-Fly Ash Admixture, 1951, (unpublished). One source of fly ash tested with clay to determine if pozzolanic action occurs as reported by other investigators. No beneficial effects noted.
14. Cooperative Study with Missouri on the Use of Monsanto Chemicals - CRD No. 186, 189, 195 and 197 as Soil Modifiers. Letter report to F. V. Reagel, April 12, 1951. Density, volume change, and strength were studied for various percentages of chemicals mixed with Missouri soil. No beneficial effects noted.
15. Exploratory Study of the Use of Chrome-Lignin Admixture, by J. A. Kelley, 1952-53, unpublished. Various quantities of potassium bichromate and lignin mixed with soil to determine effects on plasticity and strength. Admixture appeared to have possibilities.
16. Exploratory Study of the Use of Alum as an Admixture, by J. A. Kelley, 1952, unpublished. Density and volume change tests indicated that the material had very little value for stabilization.
17. Exploratory Study of the Use of Beryllium Sulphate, Lithium Sulphate and Sodium Sulphate as Admixtures, by J. A. Kelley, 1952, unpublished (limited data). Beryllium sulphate may have some characteristic that is helpful in soil stabilization.
18. Exploratory Study of the Use of Sodium Abietate Admixture, by J. A. Kelley, 1953, unpublished. No beneficial effects noted on density or strength.

APPENDIX B

Letter of Agreement for Cooperative Effort with Industrial Firms to Develop Chemical Stabilizing Treatments for Soils

This letter is to confirm our mutual understanding concerning cooperative work by your company and this agency to develop chemical stabilizing treatments for soils.

As you are aware, much has been learned regarding methods and materials for this purpose. However, available stabilization treatments vary widely in their effectiveness with different soils, and there is much room for improvement in both the quality of stabilized soil materials and the economy of construction operations. We believe that there are possibilities of developing improved chemical treatments, and we are interested in exploring these possibilities.

We would like to carry on cooperative research along these lines and have so advised you and certain other chemical companies who might be interested. We are familiar with the soils available for use in road construction and you are expert in the field of chemistry. By working together our two organizations may be able to produce a very useful end product.

Our contribution to this cooperative undertaking will include conducting laboratory evaluation studies of such chemical stabilizing agents as you may submit to the FHWA and furnishing you with reports of the results of such studies. For those chemicals which in this evaluation and in our opinion show sufficient promise of effectiveness and practical use, we shall undertake to encourage the several State highway departments to conduct appropriate field trials in order to determine their effectiveness and practicality under actual road conditions.

It is understood that we will undertake to test only those chemicals that previous development work by you has shown to have some promise. Such chemicals should be suitable for application to the soil by practicable means and their cost should be such that their use in road construction could be justified economically.

It is proposed that representatives of your company and FHWA will meet from time to time to consult with respect to this cooperative endeavor. Such consultations would involve, among other things, the review of the results of the evaluation studies, and the exchange of ideas on the improvement of techniques and consideration of the employment of new or different methods to achieve better results and to fix the direction of further research.

It is understood that your company will be entitled to retain the entire title and interest in any patent rights that may result from research and development on the part of your company in connection with this cooperative work, to the same extent that your company would have such rights independent of any testing and evaluation on the part of FHWA, and your company will not be expected to reveal any chemical formulas or other information or data that might impair its right to such protection under the patent laws.

FHWA contemplates the publication of periodic research reports on the results and evaluation of the tests. FHWA agrees not to make public any of the findings developed or made available to it under this arrangement without the Company's prior written consent unless such findings have otherwise been made available to the public. FHWA will not reveal confidential information that may happen to come into its possession pertaining to the Company's products used in the tests.

Each party shall be responsible for its own costs and expenses incurred in connection with the services and activities performed under this agreement. It is understood that either party may at any time terminate the arrangement provided for herein and upon such termination neither party shall have any obligations to the other hereunder other than the obligations of FHWA not to make public any of the findings developed or made available to it under this arrangement, and not to reveal confidential information, as provided above, which obligation shall still remain in effect.

Sincerely yours,

This confirms our understanding:

By _____ Title _____

Date _____

APPENDIX C

Chemicals and Proprietary Products Advanced as: (A) Soil Stabilizer;
(B) Compaction Aid; (C) Dust Palliative; and (D) to Control Erosion

Name of Material	Type of Use	Producer or Developer
Aerospray 52, 70	D	American Cyanamid Co.
Aliquat H-226 (quaternary amine)	A	General Mills, Inc.
AM-9	A	American Cyanamid Co.
Aniline-furfural	A	H. Winterkorn
Aquatain	D	Larutan Corp.
Arquad-2HT (quaternary amine)	A	Armour Industrial Chemical Corp.
Basic (R)	A	American Basic Chemicals, Inc.
Chrome-Lignin	A	Cornell University
ClaPak, ClaSet	A, B	Central Chemical Co.
Calcium acrylate	A	Rohm and Haas Co. (T. W. Lambe, Jr., M.I.T.)
Cellulose compounds	A	Rayonier, Inc.
Compact	B	Gra-Kote
Cyanoloc 62 (and others)	C, D	American Cyanamid Co.
Diatol (emulsified asphalt)	A	Unknown
Earth-Pak	B	Gerald C. Bower, Inc.
Fujibeton	A	Business Development International
Geoseal	A	Borden Inc.
KelPak	D	Central Chemical Co.
Kompak	B	Terra-Perma, Inc.
Lignin liquors and compounds	A, C	Rayonier, Inc. and various others
Lime, hydraulic	A	Riverton Lime and Stone Co.

APPENDIX C (continued)

Name of Material	Type of Use	Producer or Developer
Lime, waste (carbide lime from acetylene plants)	A	Chemical Lime Corp. and others
Liqui-Road	A	Humphrey Corp.
Miral-Cote	C, D	Soil Seal Corp.
Paczyme	A, B	Larutan Corp.
PDC (portland cement-lime- casein)	A	Products Development Co.
Permasteer	A	Terra-Perma, Inc.
Phosphoric acid	A	Monsanto Chemical Co.; Tennessee Corp.
Plasmofalt, Plasmosix	A	Tropical Agricultural Research Lab.
Resinol	A	Golden Bear Oil Co.
Reynolds Road Packer (Road Packer)	A, B	Zel Chemical Co.
RX-1, RX-2	A	Central Chemical Co.
SA-1	A	Central Chemical Co.
Salt (sodium chloride)	A	The Salt Institute; Morton Salt Co.
SC-50 (silicone)	A	General Electric Co.
Soil Consolid-RSP	A, B	Nacco Est.
Soilcrete	A	General American Transportation Corp.
Soil Seal	A	Soil Seal Corp.
SSA (178, 179, 180)	A	E. I. du Pont de Nemours Co., Inc.
Terbec (TBC)	A	Dow Chemical Co.
Terrabind	A	Deutsche Terrabind - Erdstabilisierings - GMBH
Terra Firmer	A, B	Construction Chemicals, Inc.

APPENDIX D

Laboratory Evaluation of Chemical Additives for Soil Stabilization

The agreement made by the Federal Highway Administration with various chemical producers for the development of chemicals for soil stabilization provides that: (1) before a chemical is submitted to the FHWA laboratory for evaluation, the chemical company will make preliminary tests on chemical-soil mixtures to determine that the chemical has potential as a stabilizer; (2) if the company's test results so indicate, FHWA will perform laboratory tests on mixtures of the submitted chemical with a variety of soils and report to the company concerning the apparent effectiveness and practical value of the chemical for treating soils; and (3) if the results of the screening tests warrant further consideration of a chemical, FHWA then assists the company in negotiations with State highway departments for the construction of experimental road sections in which the chemical is used in stabilizing subgrade or base materials.

Procedural details for the laboratory tests used in the FHWA's preliminary screening or evaluation program are given below. The company may use any of these tests in their own development and testing program but is under no obligation to do so. If experimental road sections are deemed to be warranted, these or other suitable tests may be performed with the soil materials involved in the road sections, to determine whether the additive is effective in stabilizing those specific materials and to establish appropriate rates of application.

1. Test Methods

Test methods for raw soils and soil-additive mixtures are listed in Table D-1. These methods are identified by designation numbers and, except as noted, are described in Book of ASTM Standards (American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103) and AASHTO Standard Specifications for Highway Materials and Methods of Sampling and Testing (Part II), (American Association of State Highway and Transportation Officials, 341 National Press Building, Washington, D. C. 20004).

Table D-1. Test methods

Test	AASHTO designation	ASTM designation
Moisture content	- - -	D 2216
Mechanical analysis	T 88	D 422
Liquid limit	T 89	D 423
Plastic limit and Plasticity index	T 90	D 424
Moisture-density relations	T 99 (Method A)	D 698 (Method A)
Volume change	T 190	- - -
Moisture absorption ^{1/}	- - -	- - -
Unconfined compressive strength ^{1/}	T 208	D 2166

^{1/} Specimen preparation and determination of moisture absorption are described in section 6. The moisture absorption specimens are also used for determining unconfined compressive strength, which is determined in accordance with the methods indicated in the table.

2. Soil Samples

For each soil used in the evaluation, about 40 lb. (18 kg.) of air-dry soil passing the no. 10 sieve is required. This provides sufficient material for tests on the raw soil and on soil-chemical mixtures at three rates of application. Preferably two or more soils and at least three rates are used.

3. Quantity of Additive

The quantity of chemical additive required is calculated from the number of rates of application selected and the number of soils to be tested. Some information concerning rates is usually available; normally, the manufacturer has subjected his product to preliminary screening tests, and has recommended an appropriate rate of application.

4. Apparatus

Apparatus and equipment required for performing the tests and preparing test specimens are identified and described in the books listed above, except in the case of apparatus for preparing specimens for the moisture absorption and unconfined compressive strength tests. The Harvard miniature compaction apparatus is recommended for this preparation. Specimens prepared with the Harvard apparatus are cylindrical, and are 1 5/16 in. (33.3 mm.) in diameter and 2.816 in. (71.5 mm.) in length. This recommendation is based on the following considerations: (1) the resultant specimens meet AASHTO and ASTM specimen size requirements (minimum diameter 1.3 inches; height to diameter ratio between 2 and 3); (2) the compaction process more closely resembles the kneading action of field compaction equipment than is obtained from either impact or static methods; (3) the quantity of soil required is conveniently small; and (4) the equipment is relatively inexpensive and is commercially available.

5. Calibration of the Harvard Miniature Compaction Apparatus

In order to prepare moisture absorption and unconfined compressive strength test specimens having the required standard AASHTO T 99 density, it is first necessary to calibrate the Harvard apparatus, i.e., to determine the correct number of tamps per layer and to regulate the tamper springs so that tamping pressures of 20, 30 and 40 lb. (9.1, 13.6 and 18.1 kg.) can be utilized. Normally, ten or more tamps per layer are required.

Tamping pressure regulation. Check the spring pressure by using a scale, balance or compression testing machine. Adjust the spring pressure, as needed, to give the rated value (e.g., 20 lb. or 9.1 kg.).

Tamps per layer. Prepare a soil-water mixture from approximately 1000 g. of soil and the amount of water required for the T 99 optimum moisture content. Place the mixture in a suitable container to prevent moisture loss, and remove an individual portion of about 150 g. for the first compaction trial. From this portion, compact a 5-layer specimen by the procedure given in items 1 through 5, section 6, using an arbitrary combination of number of tamps and tamper spring pressure. Remove the specimen from the mold with the ejector, slice into 3 or more pieces, and determine the actual moisture content by ASTM D 2216. Knowing the volume, the wet weight and the moisture content of the compacted specimen, compute the dry density and compare it with that from the T 99 procedure. If the dry density is not within one pound of the T 99 density, use a second portion of the moist mixture, and prepare a new specimen at another combination of number of tamps and tamping pressures, and this process is repeated with additional portions until a density is obtained that is within one pound of the T 99 density. This combination is then used in the preparation of test specimens, section 6.

6. Specimen Preparation and Test Procedure for Moisture Absorption and Unconfined Compressive Strength

Preparation of specimens for moisture absorption and unconfined compressive strength requires a quantity of about 1000 g. of soil-water or soil-additive-water mixture. In preparing this mixture in a mechanical mixer, the amount of water used should be from 0.5 to 3.0 percent in excess of that required for the optimum moisture content, to compensate for evaporation losses. The exact amount of excess water will depend on the humidity and other laboratory conditions.

Using this mixture and employing the combination of number of tamps and tamping spring pressure as determined in the calibration procedure, six test specimens are prepared and tested as directed below.

The first six items of this procedure are taken from a suggested method of test in "Special Procedures for Testing Soil and Rock for Engineering Purposes," 5th ed., STP 479, ASTM, 1970, pp 101-103.

1. With the mold and collar clamped to the base, the amount of loose soil required for one layer is placed in the mold. For a five-layer specimen, two slightly heaping teaspoonfulls will be required for each layer. Level the surface of the loose soil by pressing lightly with a wood plunger.
2. Insert the tamper in the mold until it is in contact with the surface of the soil, and press down firmly until the spring starts to compress. Release the force and shift the tamper to a new position. Each of the first four tamps should be applied in separate quadrants of the soil surface, and adjacent to the mold. The fifth tamp should be in the center, making one complete coverage. This tamping cycle is then repeated until the desired number of tamps has been applied. The tamps should be applied at the approximate rate of 10 tamps per 15 sec.
3. Add and tamp the next layer, and repeat the procedure until the required number of compacted layers has been placed. The top layer should extend at least $\frac{1}{2}$ in. (13 mm.) into the extension collar.
4. Transfer the mold assembly to the collar remover and release the clamps. Press down firmly on the piston and at the same time pull up on the handle, prying the collar loose from the compacted soil.

5. Remove the mold from the base and carefully trim away the excess soil from the top and bottom of the mold.
6. Weigh the mold containing the compacted soil to the nearest 0.1 g. It is convenient to use a tare weight equal to the weight of the empty mold, as then the resulting net weight in grams is numerically equal to the wet density of the compacted soil, in pounds per cubic foot.
7. The specimen is removed from the mold with the ejector, weighed, wrapped in plastic food-wrapping material and placed in a high-humidity chamber for the desired curing period.
8. Between the compaction of the third and fourth specimens a 100-gram sample is taken from the remaining loose mixture and the actual moisture content is determined by D 2216.
9. At the completion of the curing period, the wrapping material is removed from the specimens, the specimens are weighed, immersed in water for 2 days, removed from the water, surface-dried by blotting with a towel, and reweighed. Any gain in weight due to immersion represents the moisture absorption and is calculated and recorded for each specimen as a percentage of the dry weight of the specimen. If appreciable disintegration or slaking of an immersed cylinder occurs, accurate determination of absorbed moisture is prevented, and indicated in the record.
10. After weighing as indicated above, the specimens are tested for unconfined compressive strength in accordance with AASHTO T 208.

7. Testing Program

Following the testing of each raw soil by the several test methods listed in Table D-1 the same tests are performed on soil-chemical mixtures. For each rate of additive, five batches of soil-chemical mixture are required. A batch is prepared by combining in a mechanical mixer carefully weighed portions of soil, additive and water, blending thoroughly (normally for about 5 minutes) to produce a high degree of homogeneity. Each batch is prepared and tested separately as described below:

1. Approximately 2700 g.; determine optimum moisture and maximum density by AASHTO T 99.
2. Approximately 1000 g.; as described in the calibration procedure given above, determine with the Harvard apparatus the number of tamps and the spring pressure required to duplicate the standard T 99 density.
3. A 500 g. batch prepared at optimum moisture content; as soon as the mixing is completed, the mixture is divided into three approximately equal portions. Liquid and plastic limit tests are performed on one portion after air-drying overnight, on another after overnight storage at high-humidity, and on the other after 8 days of curing at high humidity.
4. Approximately 3600 g.; determine expansion pressure by AASHTO T 190.
5. Approximately 1000 g.; with the Harvard apparatus, prepare six 5-layer (required for acceptable homogeneity) specimens compacted to T 99 density, and determine moisture absorption and unconfined compressive strength as described in section 6.

