PROCEDURE FOR ECONOMIC DEVELOPMENT OF SOIL-CEMENT MIX DESIGN

H. H. Duval, Duval and Associates, Inc., Dallas; and
J. H. Alexander, Southwestern Laboratories, Inc., Fort Worth

ABRIDGMENT

The purpose of this paper is to provide design engineers and planning agencies with a method that incorporates economic considerations in developing the mix design of a soil-cement for highway construction. Modifications of the procedure can be made for other types of projects such as airfields, dam facings, and erosion control projects. The procedure is a step-by-step method incorporating planning, field sampling, preliminary laboratory testing, cost analysis, and final testing to develop a cement factor for construction.

• THE BASIC approach used for development of a successful soil-cement program considers two fundamental criteria: the durability and economy of structural load-carrying capacity. There have been many research projects, technical papers, standard test methods, and development of construction practices that ensure a structurally satisfactory job, but little is available in printed form to aid in the selection of economic considerations. The program that is discussed integrates both of these factors to cover the basic essentials of soil-cement construction.

Constructing soil-cement involves mixing the soil, cement, and water. Compacting, finishing, and curing complete the operation. In considering the economics involved, only a few variables are applicable: the materials to be used in the mix and the method of construction. In the material selection, water and cement are least variable from an economic standpoint. To ensure that the cement is sufficient to produce desired results requires specification of the type of cement to be used (e.g., normal Type I, conforming to ASTM C 150). Nearly all producers of cement meet this requirement. Variances in cost are normally concerned with the cost of transporting the cement. The water supply is usually specified to be free from substances that could interfere with the hardening of the soil-cement. If the water is safe for drinking, it generally meets this requirement. Again, the economic considerations generally are reduced to the cost of transportation. The third component of the mix, soil, presents a wide choice of sources or combinations of sources to achieve an economic mix design and will be discussed in detail.

METHODS OF CONSTRUCTION

There are two basic methods widely used in soil-cement construction that will produce consistently good results.

Publication of this paper sponsored by Committee on Soil-Portland Cement Stabilization.

The original manuscript on which this abridgment is based is available in Xerox form at the cost of reproduction and handling from the Transportation Research Board. When ordering, refer to XS-49, Transportation Research Record 501.

Mixed-in-Place Method

This method uses part or all of the in-place soils in the mix. After the roadway has been prepared to the lines and grades on the plans, a blanket of cement is applied to the surface corresponding to the cement factor specified for the thickness and type of soil being used. The soil and cement are mixed together by single-pass or multipass machines. Water is added and mixed in, and the mixture is compacted, shaped, and cured to complete the soil-cement process. How expensive elimination of the cost of procuring and transporting all or part of the materials is should be considered.

Central Plant Mix Method

This method must use 100 percent borrow material that is transported to the roadway in dump trucks and that is proportioned with the specified cement factor and water in a batch plant or in a continuous mix plant. The mixture is spread (through mechanical spreaders), compacted, shaped, and cured. Because of the 30-min limitation on transporting the mixture, the plant must normally be moved when the haul distance exceeds about 5 miles (8 km). The economic consideration for this method is the ease of quality control during construction.

During the investigation and evaluation of materials used for construction, both the in-place and central plant mix method should be considered to determine the economics involved. If there is not a great deal of difference, the contractors should be permitted to bid them as alternates.

SOILS

It has been claimed that there are more different soils in the world than there are people. This might present us with an insurmountable task for selecting the most economic soil for a given project. Fortunately, however, the total range of soils can be broken down into a few groupings by physical and mineral characteristics that greatly simplify the problem. Each group requires a limited range of cement factors that can be determined by standard test methods. Better than 80 percent of the earth's soils or soil mixtures can be treated successfully with less than 12 percent cement. The design engineer must select from the soils available to him that soil, or combination of soils, which will produce the desired results by balancing the three cost factors involved with that soil:

1. Cost of buying, excavating, and transporting soil;
2. Physical properties of the soil that affect the costs of mixing, compacting, and finishing; and
3. The cost of the amount of cement necessary to give the mixture the desired structural properties.

TYPES OF CEMENT STABILIZATION

There are several classifications of cement stabilization, which are intended to solve a particular problem for the design engineer. They all follow many of the same procedures for testing and evaluation. All are based on the performance of the end product, which, of course, involves the properties of structural strength and durability. The amount of cement required to satisfy these requirements has been developed into standard testing methods adopted by ASTM and AASHTO.

Soil-Cement

Soil-cement is the most commonly used type of cement stabilization. It is intended to be a hard, durable, structural element of a pavement structure that fits somewhere between the load-carrying characteristics of flexible or rigid pavements. It is normally called a semirigid or semiflexible pavement. It is used as a base course under an asphalt wearing surface or as a subbase under a concrete pavement. Because of the abrasion losses from traffic, it should never be used as a wearing surface.

The performance of soil-cement, used as either a base or subbase, has been standardized through research and field evaluation. Regardless of the type of soil used, standard laboratory tests can develop the structural strength and durability desired. In other words, this standard of performance for over 80 percent of the earth's soils can be achieved in the laboratory by varying the amount of cement to meet the requirements.

Cement-Treated

Cement-treated, rather than soil-cement, denotes use of a better grade of soil aggregate in the mix. This is normally a pit-run or river-run gravel with a cement content that produces a higher strength and more durability. Cement treatment is normally used as a subbase under concrete pavement for high-density jet airports. The testing and construction procedures are the same as for soil-cement.

Plastic Soil-Cement

Where restricted construction areas prevent the use of normal construction equipment, some use of soil-cement has been made to overcome this rather specialized situation. Sufficient water is added to the mix to permit placement and finishing in much the same manner as that used for concrete. The tests for determining the cement content are run in a plastic state with the addition of 4 percent cement added to offset the lack of density that results from the excess water used in placement.

Cement-Modified Soil

This classification of cement-stabilized soils is limited to changing some of the physical properties of a soil, and it does not result in a hard, durable structural element. Normally, cement-modified soil is used in much the same manner as lime treatment. Either hydrated lime or cement can be used to lower the plasticity index of a plastic subgrade soil to correct deficiencies in the subgrade and to provide a building platform for subsequent pavement layers. In a highly plastic soil, subject to high volume change, cement-modified treatment, like lime treatment, will provide a relatively impervious layer. This will permit the groundwater to reach a state of substantial equilibrium so that the volume change can take place before subsequent structural pavement layers are applied. In design, it is a good practice not to assign a structural load-carrying capacity to a layer for purposes of reducing the subsequent pavement thickness. This layer is normally considered only as an improved subgrade. The test procedures to determine the amount of cement to be used depend on those properties of the soil that the design engineer wants to modify. As an example, to reduce the PI of a clay, the Atterberg limits test would be run with different amounts of cement to determine the best cement content to achieve the desired results.

Soil-Cement Revetments

In recent years, soil-cement has been used much more for erosion control, ditch linings, levee construction, and dam facings. Because these uses are not subject to abrasion by traffic, they normally require no wearing surface. Tests to determine the cement content to be used are the same as those used for normal soil-cement. Two percent cement is added for structure areas subject to wetting and drying cycles and wave action.

Because soil-cement, used as a base or subbase for highways, airports, streets, and parking areas, is by far the most commonly used type of cement stabilization, the discussion will be directed to a procedure for the mix design that is applicable to this process. To arrive at the most economical pavement structure requires that two variables be evaluated: (a) soils to be used in the mixture, and (b) the method of construction. These two variables are interdependent, with the selection of the soils probably being the more important for the sake of economy.

PROGRAM FOR MIX DESIGN

Soils Evaluation

The design of the mix to be used for construction will follow a procedure of laboratory tests, evaluation of costs, and a study of data developed previously.

Use of Available Data—When the design engineer has decided to use soil-cement for a particular highway project, several tools will be available that should prove very useful for selecting materials for construction:

1. Aerial photographs and topographic, geological, Agricultural Soils Association, and soils series maps are useful in identifying soils in the highway right-of-way and for the location of prospective borrow pits.
2. The soils boring program establishes subgrade bearing values for design.
3. Visual inspection of cuts along the right-of-way, showing the soil profile, and inspection of existing borrow pits and riverbeds should help develop an overall picture of materials available in the highway area.

Tables of average cement contents for different soils can be found in the Soil-Cement Laboratory Handbook, published by the Portland Cement Association. From these tables, one can see that the better graded granular soils require far less cement than do silts and clays for the same standard of load-carrying capacity and durability. Possibly there could be well-graded, granular soils in the roadbed, but this does not occur often, except in an old, granular-base road that is to be reconstructed with soil-cement. More often, the existing subgrade will consist of a material that, by itself, cannot be treated as economically as a borrow soil or a combination of a borrow soil and the in-place soil.

Cement Versus Soil Gradation—To better understand the factors that determine the amount of cement required for a soil, it helps to picture what takes place with several different types of soil. First, in the case of a well-graded, pit-run gravel (AASHTO A-1-a), 3 to 5 percent cement normally will provide the desired strength and durability. The makeup of this soil has just enough of each size of soil particle, from gravel size to sand, silt, and clay sizes, to fill most of the voids when the mass is compacted to a high density. In this condition, then, very little cement is required to permanently cement one soil particle to another. In the case of a uniformly graded sand (AASHTO A-3), the cement contents range from 7 to 11 percent, which is more than double the cement required for an AASHTO A-1-a soil. This results because considerable amounts of voids between soil particles after compaction must be filled with cement if the soil particles are to be cemented together.

In the case of a fine-grained soil, clay (AASHTO A-7-5 or A-7-6), the cement contents range from 13 to 16 percent. The soil has far more soil particles than the same mass of a well-graded gravel. More cement is required to stick all of these fine particles together. Because the amount of cement required for any particular soil is a function of the gradation of that soil, it is easy to see that any improvement of the gradation will result in a lower cement factor. Take the case of an existing, uniform sand in the roadway that requires 7 to 11 percent cement (AASHTO A-3) and an available borrow pit with a clay sand (AASHTO A-2-6) that requires 5 to 9 percent cement. If these soils were blended together, using 50 percent of each, an improvement of both soils that would require about 4 to 8 percent cement would result.

Planning of Economic Mixes

Obviously, the more material in place in the roadway that is suitable for the mixture, the less costly the mixture will be. However, use of in-place soils also dictates that the construction procedure must use mixed-in-place construction. More commonly, all borrow soils used are from pits located on or near the project. It all boils down to balancing the cost factors involved in acquiring and handling soils versus the cost of the cement required.

Procedure for Selection, Testing, and Evaluation of Materials

A workable method for selection of materials to be considered for final mix designs follows:

1. Evaluate existing data from sources previously discussed (e.g., soils maps, aerial photographs) to determine locations of prospective materials to be sampled and tested.
2. Send a field crew out to selected locations to obtain representative samples from each site.
3. Perform preliminary laboratory tests consisting of gradation, Atterberg limits, and standard AASHTO moisture-density relationships.
4. Make combinations of soils, from results of preliminary tests, that will improve the properties of each.
5. Mold sets of three cylinders each at 6 percent cement for each prospective mix, cure for 7 days, and break to determine the average compressive strength for each set of cylinders. Normally, a compressive strength of less than 200 psi would eliminate any of the prospective mixtures from further consideration. (For silts or clays, a higher cement factor can be used.)
6. Submit the remaining prospective mixtures to the shortcut test method for sandy soils.
7. Estimate the costs from the results of this test to determine the most economical mixtures for further consideration.
8. Determine the cement factor to be used for construction by testing the remaining one or two mixtures for each given section of the project with the standard ASTM or AASHTO method.

Inasmuch as most soils can be adequately hardened to produce a given standard of structural strength and durability by varying the amount of cement, it follows that economics will be the deciding factor. For sizable projects, it is certainly worth the time, effort, and expense to logically evaluate all the materials that show a promise for use in construction.

Tests for Economic Mix

The use of a simple compressive strength test using 6 percent cement enables the engineer to substantially reduce the overall testing program. The soil mixes above a compressive strength of 200 psi are now run through the shortcut test method for sandy soils.

This test provides a safe cement factor for the soil mixes that may be the minimum cement factor possible or 1 to 3 percent above it. There is no way to determine the minimum cement factor used in construction without running the standard ASTM or AASHTO test for wet-dry and freeze-thaw (ASTM D559-57 and D560-57 and AASHTO T135-57 and T136-57). The difference between 1 and 3 percent cement for large projects can be considerable for cement that is not necessary for the quality of the end product. Therefore, the cement factor for the final mixture must be determined by these tests to achieve the most economic mixture. To complete the 12 cycles required for these tests normally takes between 6 and 8 weeks. To run more than the most promising mixtures through this phase of testing would be a waste of time, effort, and money. This hypothetical project, like most projects, has many prospective mixtures that could be used in construction, and elimination of all but the most promising from the time-consuming and costly standard tests is desirable.

Elimination can be accomplished readily with a simplified cost analysis based on the comparative cement factors, developed in the shortcut test for sandy soils, and on the projected costs of materials delivered to the job.

Because we are still in the preliminary phase of the investigation, we assume that samples of soils taken substantially represent the materials in the roadway and in the selected borrow pits. It is now advisable to substantiate these assumptions for both the quality and quantity of the materials to meet the project requirements.

This requires a more thorough investigation of the two borrow pits selected and of the soils in the roadway. A recommended procedure to test a prospective borrow pit is to take undisturbed samples, with Shelby tubes or split-spoon samples with a sufficient number of borings to effectively determine the limits of the desirable materials in the pit. From this boring log, the soil profile of the pit can be drawn, and a calculation made of the quantity of materials available. Analysis of the soil profiles establishes the basic requirements the contractor must follow in excavating the borrow pit to ensure that materials taken from the pit have the same proportions from each horizon or layer as those used in mix design testing.

Boring is performed on the undisturbed samples to be used in the mixture to prove that the materials in the roadway are substantially the same as those used in the mix design test. Normally, this program consists of borings every 300 to 500 ft (90 to 150m) in a staggered pattern—right side, centerline, left side, centerline, right side, and so on. If there is an apparent soil change between borings, the area of change is determined by intermediate borings. If the changed areas are relatively minor, it is most often more economical to undercut and remove a soil that would require more cement than it is to change the cement factor for a short distance.

Final mix design samples are collected from the borrow pits and the roadway and are combined in the same proportions as those used in the preliminary mix design to see if their physical characteristics agree with those of the original testing.

The normal project calls for payment for cement as a separate bid item. This eliminates the gamble, on the part of the contractor, for the amount of cement used in construction and makes the engineer responsible for determining what material will be used and what cement factor will be required for construction. To put this responsibility on the contractor would necessitate duplicate laboratory testing programs that would increase the cost of the project, in addition to requiring the contractor to hire the personnel or equipment to perform this phase of engineering design.

Final Mix Design

We have established the sources and mixtures of materials used in construction and we must now determine the most economical cement factor to be used. For the average soil-cement project, the wet-dry and freeze-thaw tests, as established in ASTM and AASHTO procedures, will prove adequate for construction. The results of the tests take into account minor variations, soil conditions, and construction methods. During a construction project, the contractor should perform the work substantially within the limits specified. However, it is unreasonable to expect that these limits will not be occasionally violated. Construction specifications are regarded as a guide, and minor variations are expected and are accounted for in mix design testing.

Laboratories that are not equipped with apparatus to perform the freeze-thaw test often substitute a minimum compressive strength test in lieu of the freeze-thaw test. A workable criterion in this case would be to run the wet-dry test in conjunction with an unconfined compressive strength test requiring a minimum strength of 350 psi at 7 days.

Procedures to Be Avoided

Experience indicates a few factors in mix design testing and evaluation procedures that should be avoided to assure a successful construction project.

1. The engineer should insist that laboratory tests be run to determine the cement factor. Guessing at a proper cement factor or assuming that tests run on a similar soil will require the same amount of cement without check testing is very dangerous. It is better not to use soil-cement unless an adequate testing program is used in the mix design and unless there is quality control of construction.

2. Testing procedures are all based on the widely used normal soils test: the moisture-density relationship (ASTM D 558-57 and AASHTO T 134-57). This calls for a standard compactive effort using a $^1/_{30}$-ft^3-capacity Proctor mold with three layers compacted at 25 blows per layer with a $5^1/_2$-lb hammer falling 12 in. Basic research to determine the cement factor has been based on this compaction. It can be disastrous to assume that, if standard AASHTO compaction is adequate, modified

AASHTO is better for the mix design test. With most soils, a 1 to 3 percent lower cement factor will be indicated with a modified AASHTO compactive effort; this can cause failures in the construction phase.

3. Locally developed tests that are substantiated by PCA, ASTM, and AASHTO standards should be avoided.

4. The most economical soil mixtures generally fall into the granular material category. Heavy clays are impractical because they require a high cement factor and are difficult to adequately mix with cement. Pretreating a high-PI clay with hydrated lime can eliminate the disadvantages in extreme cases where granular soils are not available. Organic topsoils are normally avoided; however, they, too, can be used by neutralizing the harmful effects of the organic acids with an additive of calcareous material such as calcium chloride.

Testing procedures to determine the most economical cement factor for construction are easy to use and give consistently reliable results. Following the described investigation program to accompany these test procedures should produce a project that is not only satisfactory structurally but also economically.