A2J01: Committee on Cementitious Stabilization
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Cementitious Stabilization

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The principal materials used for the cementitious stabilization and modification of highway pavement materials are lime, fly ash, and portland cement. Whereas lime and portland cement are manufactured products, fly ash is a by-product of the burning of coal at electric power generating stations. As a consequence, fly ash generally exhibits greater variability than is seen in the other products. By-products such as kiln dust and fluidized bed ash from various manufacturing and energy generating processes are used to a lesser extent. While all of these products and by-products are used for similar purposes, different testing, design, construction, and quality assurance/quality control (QA/QC) methodologies have been developed for each.

Stabilization projects are almost always site-specific, requiring the application of standard test methods, along with fundamental analysis and design procedures, to develop an acceptable solution. As with any such process, adherence to strict environmental constraints is vital to project success. The use of cementitious materials makes a positive contribution to economic and resource sustainability because it allows enhancement of both standard and substandard in situ soils to levels consistent with the requirements of a given application.

LIME STABILIZATION

Lime stabilization is a widely used means of chemically transforming unstable soils into structurally sound construction foundations. Lime stabilization is particularly important in road construction for modifying subgrade soils, subbase materials, and base materials. The improved engineering characteristics of lime-treated materials provide important benefits to both portland cement concrete (rigid) and asphalt (flexible) pavements.

Lime stabilization creates a number of important engineering properties in soils, including improved strength; improved resistance to fracture, fatigue, and permanent deformation; improved resilient properties; reduced swelling; and resistance to the damaging effects of moisture. The most substantial improvements in these properties are seen in moderately to highly plastic soils, such as heavy clays. Although lime is generally used to transform fine-grained soils permanently, it may be used for shorter-term soil modification—for example, to provide a working platform at a construction site.

Reaction Mechanisms

Soil–lime reactions are complex; however, understanding of the chemistry involved and results of field experience are sufficient to provide design guidelines for successful lime treatment of a range of soils. The sustained (and relatively slow) pozzolanic reaction between lime and soil silica and soil alumina (released in the high-pH environment) is key to effective and durable stabilization in lime–soil mixtures. Mixture design procedures that secure this reaction must be adopted.

In addition to stabilizing materials, lime plays an increasing role in the reclamation of road bases. Lime has been used effectively to upgrade or reclaim not only clay soils, but also clay-contaminated aggregate bases and even calcareous bases that have little or no appreciable clay. Work in the United States, South Africa, and France has established the benefits of lime stabilization of calcareous bases. The process results in significant improvements in strength, moisture resistance, and resilient modulus without transforming the calcareous bases into rigid systems that could be susceptible to cracking and shrinkage.

Mixture Design, Pavement Design, and Performance Considerations

Design of lime-stabilized mixtures is usually based on laboratory analysis of desired engineering properties. Several approaches to mix design currently exist. In addition to engineering design criteria, users must consider whether the laboratory procedures used adequately simulate field conditions and long-term performance. Aspects of these procedures are likely to be superceded as the American Association of State Highway and Transportation Officials (AASHTO) shifts to a mechanistic-empirical approach.

Laboratory testing procedures include determining optimum lime requirements and moisture content, preparing samples, and curing the samples under simulated field conditions. Curing is important for chemically stabilized soils and aggregates—particularly lime-stabilized soils—because lime–soil reactions are time and temperature dependent and continue for long periods of time (even years). Pozzolanic reactions are slower than cement-hydration reactions and can result in construction and performance benefits, such as extended mixing times in heavy clays (more intimate mixing) and autogenous healing of moderately damaged layers, even after years of service. On the other hand, longer reactions may mean that traffic delays are associated with using the pavement. In addition, protocols for lime–soil mixture design must address the impact of moisture on performance.

Lime stabilization construction is relatively straightforward. In-place mixing (to the appropriate depth) is usually employed to add the proper amount of lime to a soil, mixed to an appropriate depth. Pulverization and mixing are used to combine the lime and soil thoroughly. For heavy clays, preliminary mixing may be followed by 24 to 48 hours (or more) of moist curing prior to final mixing. This ability to “mellow” the soil for extended periods and then remix is unique to lime. During this process, a more intimate mixing of the lime and the heavy clay occurs, resulting in more complete stabilization. For maximum development of strength and durability, proper compaction is necessary; proper curing is also important. Other methods of lime stabilization include in-plant mixing and pressure injection.

Information Gaps

The performance of lime-stabilized subbases and bases has been somewhat difficult to assess in the current AASHTO design protocol because the measure of structural contribution—the structural layer coefficient—cannot be ascertained directly. Indirectly determined coefficients for lime-stabilized systems, however, have been found to be structurally significant. As AASHTO shifts to a mechanistic-empirical approach, measurable properties, such as resilient moduli, will be used to assess stress and strain distributions in pavement systems, including stabilized bases and subbases. These properties will be coupled with shear strength properties in assessing resistance to accumulated deformation.

The lime industry has submitted a three- to four-step design and testing protocol to be considered for inclusion in the AASHTO design protocol:

- Step 1—Determine optimum lime content using the Eades and Grim pH test.
- Step 2—Simulate field conditions. Use AASHTO T-180 compaction and 7-day curing at 40º C to represent good-quality construction techniques. After curing, subject samples to 24 to 48 hours of moisture conditioning.
- Step 3—Verify compressive strength, stiffness, and moisture sensitivity. Measure unconfined compressive strengths using ASTM D-5102 methods.

For most applications, the above three steps are sufficient because design parameters such as flexural strength, deformation potential, and stiffness (resilient modulus) can be approximated from unconfined compressive strength. For more detailed (Level 2) designs, a direct measure of resilient modulus may be required:

- Step 4—Perform resilient modulus testing using AASHTO T-294-94 or expedited (and validated) alternatives, such as the rapid triaxial test.

This protocol and its mechanistic-empirical basis provide a sound foundation for future lime-stabilization applications. Work is likely to continue on field validation of this protocol, and on expedited and simpler testing procedures to facilitate use of the protocol in creating optimum engineering designs that employ lime stabilization. Work is also expected to continue on the development of a quick and simple test for assessing moisture and freeze/thaw resistance that can be linked to field testing, such as dielectric testing in the laboratory linked to ground-penetrating radar in the field. Current test results are promising.

COAL FLY ASH STABILIZATION

Stabilization of soils and pavement bases with coal fly ash is an increasingly popular option for design engineers. Fly ash stabilization is used to modify the engineering properties of locally available materials and produce a structurally sound construction base. Both non-self-cementing and self-cementing coal ash can be used in stabilization applications.

Stabilization with Non-Self-Cementing Coal Fly Ash

Fly ash produced from the combustion of bituminous, anthracite, and some lignite coals is pozzolanic but not self-cementing. To produce cementitious products, an activator such as portland cement or lime must be added. Non-self-cementing fly ash can be used to produce a lime/fly ash/aggregate (pozzolanic-stabilized mixture [PSM]) road base. The mixture developed must possess adequate strength and durability for its designated use, be easily placed and compacted, and be economical.

Quality mixtures have been produced with lime content ranging from 2 to 8 percent (by weight). Fly ash content may range from 8 to 15 percent (by weight). Typical proportions range from 3 to 4 percent lime and 10 to 15 percent fly ash. When needed, 0.5 to 1.5 percent portland cement can be used to accelerate the initial strength gain. The resulting material is similar to cement-stabilized aggregate base in its production, placement, and even appearance.

PSM bases can be placed with conventional equipment and used with recycled base materials. The cost of PSM bases varies significantly from area to area, but is often lower than that of alternative base materials. PSM bases are not heated and require less energy to place than asphaltic bases.

The strength development of a PSM is highly dependent on curing time and temperature. In many cases, minimum curing times are specified, along with an allowable curing temperature range that will produce the required strengths. Target strengths for mix design development should allow for the fact that PSM bases will continue to gain significant strength after the curing period has ended. PSM bases also have the inherent ability to heal or recement across cracks if moisture is present, and if unreacted lime and fly ash are available. This phenomenon is known as autogenous healing. The deleterious effects of shrinkage cracks may be reduced in PSMs designed to produce slower rates of pozzolanic reaction over longer periods of time.

Stabilization with Self-Cementing Fly Ash

With the passage of the Clean Air Act in the 1970s, many utilities began burning low-sulfur subbituminous coals. An unexpected benefit of burning this lower-sulfur coal was the production of a new type of fly ash, designated by ASTM as Class C coal fly ash. This material is self-cementing because of the presence of calcium oxide (CaO) in concentrations typically ranging from 20 to 30 percent. Most of the CaO in Class C fly ash, however, is complexly combined with pozzolans, and only a small percentage is “free” lime. This characteristic may impact the suitability of the material for stabilization of plastic clay soils.

Subbituminous coals are now shipped by rail to power plants throughout the United States, although the largest concentrations of subbituminous coal combustion are west of Ohio. Class C fly ashes are shipped by truck and rail into many construction markets throughout the United States. According to ASTM D 5239, “Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization,” the use of self-cementing fly ash can result in improved soil properties, including increased stiffness, strength, and freeze-thaw durability; reduced permeability, plasticity, and swelling; and increased control of soil compressibility and moisture.

Although these ashes have properties similar to those of portland cement, they also have unique characteristics that must be addressed by both the mix design and construction procedures. The primary design consideration is the rate at which the fly ash hydrates upon exposure to water. Recognizing and properly addressing the hydration characteristics of the ash can result in a significant enhancement of the potential benefits of its use.

Even self-cementing ashes can be enhanced with activators such as portland cement or hydrated lime. This is particularly true if the self-cementing ash does not have enough free lime to develop the pozzolanic reaction potential fully. Lime or cement also can be added to self-cementing ashes to produce PSMs. A significant example of using both lime and cement as activators with Class C fly ash is the lime cement–fly ash (LCF) runway 9-27 at Houston’s Intercontinental Airport. LCF forms the runway’s major structural layer.

Mix Design and Construction Considerations

To achieve optimum results, a thorough understanding of the influence of the compaction delay time and moisture content of the stabilized materials is essential. Ash hydration begins immediately upon exposure to water. Strict control of the time between incorporation of the fly ash and final compaction of the stabilized section is required. A maximum delay time of 2 hours can be employed if contractors are not experienced in ash stabilization or if achieving maximum potential strength is not a primary consideration for the application. A maximum compaction delay of 1 hour is commonly specified for stabilization of pavement base or subbase sections when maximum potential strength is required. Achieving final compaction within the prescribed time frame generally requires working in small, discrete areas, an approach that differs from the methods used for lime stabilization.

The second major design consideration is that there is an optimum moisture content at which maximum strength will be achieved. This optimum moisture content is typically below that for maximum density—often by as much as 7 to 8 percent. The strength of the stabilized material can be reduced by 50 percent or more if the moisture content exceeds the optimum for maximum strength by 4 to 6 percent. An understanding of both the influence of compaction delay and moisture control of the stabilized material is essential to achieving the optimum benefit from stabilization applications that use self-cementing fly ashes.

PORTLAND CEMENT STABILIZATION

Since 1915, more than 100,000 miles of equivalent 7.5 m (24 ft) wide pavement bases has been constructed from cement-stabilized soils. Cement has been found to be effective in stabilizing a wide variety of soils, including granular materials, silts, and clays; by-products such as slag and fly ash; and waste materials such as pulverized bituminous pavements and crushed concrete. These materials are used in pavement base, subbase, and subgrade construction.

Definitions and Applications

Cement-stabilized materials generally fall into two classes—soil-cement and cement-modified soil.

Soil-cement is a mixture of pulverized soil material and/or aggregates, measured amounts of portland cement, and water that is compacted to a high density. Enough cement is added to produce a hardened material with the strength and durability necessary to serve as the primary structural base layer in a flexible pavement or as a subbase for rigid pavements. Cement-treated aggregate base and recycled flexible pavements are considered soil-cement products.

Cement-modified soil is a soil or aggregate material that has been treated with a relatively small proportion of portland cement (less cement than is required to produce hardened soil-cement), with the objective of altering undesirable properties of soils or other materials so they are suitable for use in construction. Cement-modified soil is typically used to improve subgrade soils or to amend local aggregates for use as base in lieu of more costly transported aggregates. Alternative terms include cement-treated or cement-stabilized soil or subgrade.

Stabilization Mechanisms

Portland cement is composed of calcium-silicates and calcium-aluminates that, when combined with water, hydrate to form the cementing compounds of calcium-silicate-hydrate and calcium-aluminate-hydrate, as well as excess calcium hydroxide. Because of the cementitious material, as well as the calcium hydroxide (lime) formed, portland cement may be successful in stabilizing both granular and fine-grained soils, as well as aggregates and miscellaneous materials. A pozzolanic reaction between the calcium hydroxide released during hydration and soil alumina and soil silica occurs in fine-grained clay soils and is an important aspect of the stabilization of these soils. The permeability of cement-stabilized material is greatly reduced. The result is a moisture-resistant material that is highly durable and resistant to leaching over the long term.

Mix Design Considerations

Mix design requirements vary depending on the objective. Soil-cement bases generally have more stringent requirements than cement-modified soil subgrades.

For soil-cement bases, two types of testing have typically been used—durability tests and strength tests. The Portland Cement Association has developed requirements for AASHTO soils A-1 to A-7 that make it possible to determine the durability of cement on the basis of maximum weight losses under wet-dry (ASTM D559) and freeze-thaw (ASTM D560) tests. Many state departments of transportation (DOTs) currently require minimum unconfined compressive strength testing (ASTM D1633) in lieu of these durability tests. This requirement is often based on many years of experience with soil-cement. The advantage of using these strength tests is that they can be conducted more rapidly than the durability tests (7 days vs. 1 month) and require less laboratory equipment and technician training. However, achievement of a specified strength does not always ensure durability. Typical minimum strength varies from 200 to 750 pounds per square inch.

For cement-modified soils, the engineer selects an objective and defines the cement requirements accordingly. Objectives may include one or more of the following: reducing the plasticity index (Atterberg limits, ASTM D4318); increasing the shrinkage limit; reducing the volume change of the soil (AASHTO T116); reducing clay/silt-sized particles (hydrometer analysis); meeting strength values/indexes such as the California Bearing Ratio (ASTM D1883) or triaxial test (ASTM D2850); and improving resilient modulus (ASTM D2434). Cement has been incorporated successfully into soils in the field with plasticity indexes ranging as high as 50.

Construction Considerations

Construction of soil-cement and cement-modified soil is normally a fast, straightforward process. Cement can be incorporated into soil/aggregate in a number of ways. The most common method is to spread dry cement in measured amounts on a prepared soil/aggregate and blend it in with a transverse single-shaft mixer to a specified depth. Cement slurries—in which water and cement are combined in a 50/50 blend with a slurry-jet mixer or in a water truck with a recirculation pump—have been used successfully to reduce dusting and improve mixing with heavy clays. Sometimes, central mixing plants are employed. Twin-shaft continuous-flow pugmills are most common, although rotary-drum mixers have been used as well.

Although construction procedures are similar for soil-cement and cement-modified soil, pulverization requirements need to be adjusted accordingly. The recommended pulverization for both granular and fine-grained soil (for soil material exclusive of gravel or stone) is as follows:

Sieve Size	*Soil-Cement*	*Cement-Modified Soil*
45 mm (1 3/4 in.)	-	100
25 mm (1 in.)	100	-
4.75 mm (#4)	80	60

Compaction is normally a minimum of 95 percent of either standard or modified proctor density (ASTM D588 or ASTM D1557, respectively), with moisture content ±2 percent of optimum.

Soil-cement shrinks as a result of hydration and moisture loss. Shrinkage cracks develop in the base, and can reflect through thin bituminous surfaces as thin (< 3 mm [1/8 in.]) cracks at a spacing of 2 m (6 ft) to 12 m (40 ft). If proper construction procedures are followed, shrinkage cracks may not reflect through, and if they do, they generally pose no performance problem. However, cracks can compromise performance if they become wide and admit significant moisture. A number of techniques have been used to minimize this problem, including compaction at a moisture content slightly drier than optimum; precracking through inducement of weakened planes or early load applications; delayed placement of surface hot mix; reduced cement content; and use of interlayers to absorb crack energy and prevent further propagation.

AREAS FOR FURTHER RESEARCH

Despite many years of stabilization with cementitious materials, challenges remain in the optimal use of these materials within an evolving mechanistic design framework. These challenges include developing a better understanding of the long-term performance of the stabilized element and using QA/QC procedures that are effective predictors of long-term performance. Research is needed at all levels—basic, applied, and demonstration. Fundamental research is needed to understand cementitious reactions and their short- and long-term roles in the stabilization process.

Given that many state DOTs now use compressive strength testing as the sole criterion for determining cement content in soil-cement, additional research is needed to ensure that durability is also achieved at the specified strength for a variety of soil types. New durability tests may need to be developed for this purpose. A rapid and reliable test for assessing the impact of wet/dry and freeze/thaw cycles on durability remains a key need as well.

Also, as cracking appears to be the greatest performance concern, further research is needed to confirm the applicability of the techniques discussed above for various soil types. Particularly promising is the use of precracking techniques, which can be as simple as applying a vibratory roller 24 to 48 hours after final compaction.

Finally, the rehabilitation of existing flexible pavements has become increasingly important, as has the need to minimize disposal and conserve aggregate supplies. Therefore, cement-recycled flexible pavements that incorporate asphalt surfaces, bases, and underlying subgrades need to be monitored in controlled field applications. Performance criteria, standardized design and construction techniques, and specifications need to be developed to better guide industry practitioners in producing high-quality recycled road bases.