KILN DUST-FLY ASH SYSTEMS FOR HIGHWAY BASES AND SUBBASES

Research, Development, and Technology

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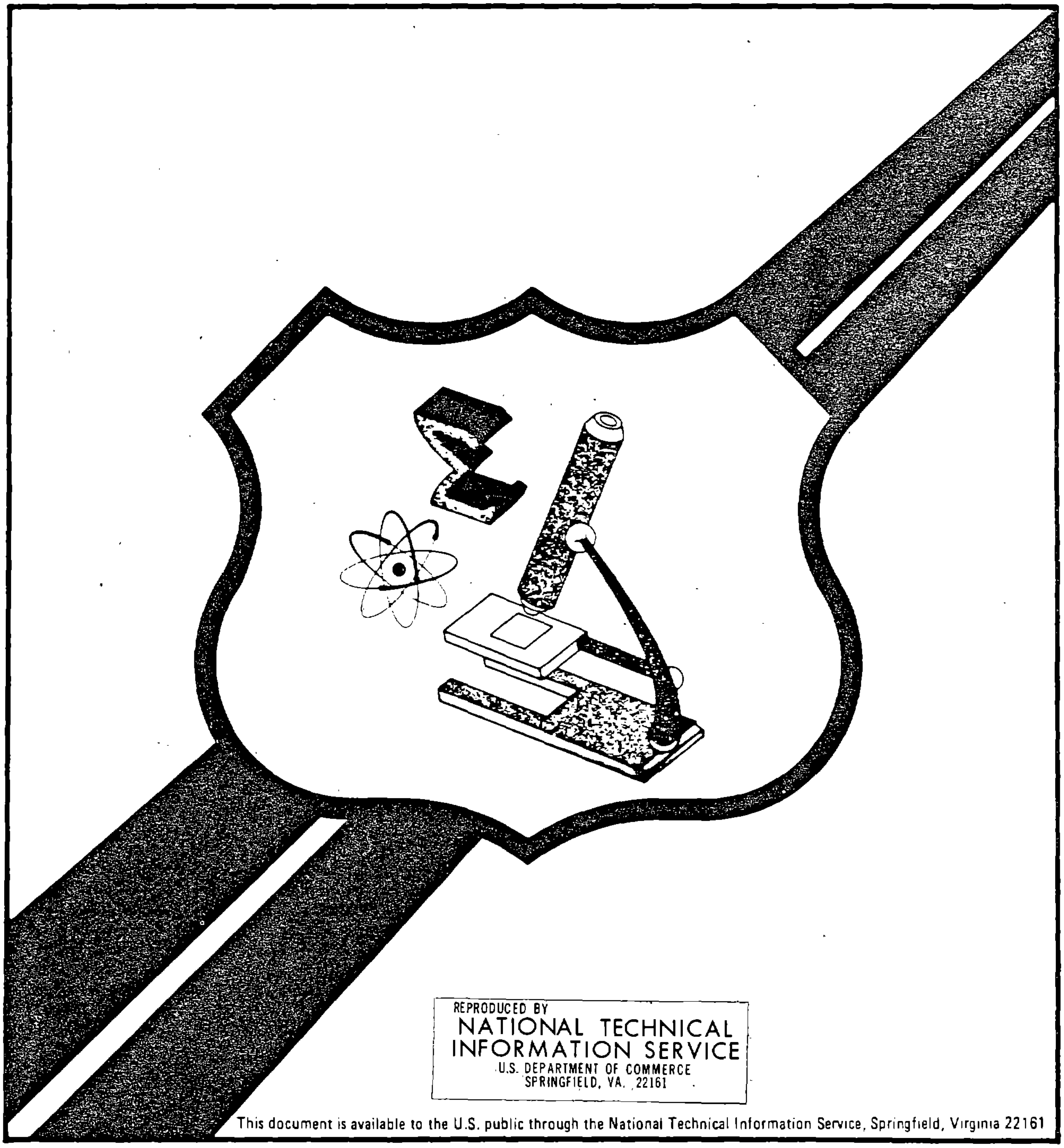
McLean, Virginia 22101

Report No.
FHWA/RD-82/167

U.S. Department
of Transportation

Federal Highway Administration

Final Report
September 1983



Technical Report Documentation Page

1. Report No.
FHWA/RD-82/167

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Kiln Dust-Fly Ash Systems for Highway Bases and Subbases

5. Report Date
September 1983

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)
36C2-242

11. Contract or Grant No.
DTFH61-81-C-00037

12. Sponsoring Agency Name and Address
U.S. Department of Energy and
U.S. Department of Transportation
Federal Highway Administration
Washington, D.C.

13. Type of Report and Period Covered
Final Report
February 1981-October 1982

14. Sponsoring Agency Code
CME/0040

15. Supplementary Notes
FHWA Contract Manager: Donald Fohs HNR-30

16. Abstract
Production of lime and portland cement results in the annual generation of more than 20 million tons of kiln dust, mostly cement kiln dust. The purpose of this investigation was to determine the effectiveness of substituting kiln dusts for hydrated lime in lime-fly ash-aggregate road base systems.

A total of 45 kiln dust samples, including 33 cement dusts and 12 lime dusts, were obtained in accordance with a standard sampling procedure. In addition, 18 fly ashes (including 5 Class C ash samples) and 6 aggregates were included in the sampling program.

Kiln dust and fly ash samples were characterized by Trow, Ltd. to determine physical properties and chemical, as well as mineralogical, composition. Optimum kiln dust-fly ash ratios were developed for 66 mix combinations. Kiln dust-fly ash-aggregate compressive strength tests were performed. Engineering properties (durability, volume stability, etc.) of optimum mix combinations were tested and compared with conventional lime-fly ash-aggregate mixtures. Most kiln dust-fly ash-aggregate mixes were comparable to, and in many cases demonstrated higher early strength development than, lime-fly ash-aggregate mixes.

Optimum mix strengths for kiln dust-fly ash-aggregate compositions were generally attained at kiln dust-fly ash ratios of 2:1 using cement kiln dust and 1:1 using lime kiln dust. By contrast, most lime-fly ash-aggregate mixes have lime-fly ash ratios of 1:3 or 1:4. Therefore, higher concentrations of kiln dust are required compared to commercial lime. Mixes containing Class C fly ash developed higher strengths than comparable mixes with Class F fly ash.

17. Key Words
Kiln Dust
Fly Ash
Stabilization
Road Base
Highway
Construction
Cement
Lime

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)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	135	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

TABLE OF CONTENTS

FOREWORD

This report presents the results of a laboratory study conducted by Valley Forge Laboratories under contract DTFH61-81-00037 to evaluate the effectiveness of substituting kiln dusts derived from the manufacture of portland cement or lime for hydrated lime in lime-fly ash-aggregate (LFA) road base systems. It will be of interest to materials and pavement design engineers.

This research study, sponsored by the Department of Energy, was conducted to identify the physical, chemical and mineralogical characteristics of kiln dusts indicative of their suitability for use in the base system.

The results indicate that the majority of the kiln dusts react with fly ash and aggregate to provide a base material with strength, durability, dimensional stability and other engineering properties equal to those of conventional LFA mixtures.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of one copy to each FHWA regional office and two copies to each State highway agency. Direct distribution is being made to the division offices.

Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development

NOTICE

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

ACKNOWLEDGMENTS

The authors are grateful to the Federal Highway Administration contract manager for providing significant technical support and inspiration. Special thanks are due to personnel from cement and lime companies, utility companies, ash marketing organizations, and aggregate producers for collecting and furnishing the material samples used in this testing program. The assistance of trade association representatives from the portland cement, lime, fly ash, crushed stone, and sand and gravel industries is also greatly appreciated.

Sincere gratitude is expressed to Dr. L. John Minnick, who served as project consultant, for his advice in arranging for lime kiln dust samples and for his review of the data and report draft. Thanks are also extended to Richard H. Miller of Valley Forge Laboratories for assistance in the testing program and review of data and report. The authors also wish to acknowledge Dr. William A Kneller of the Eitel Institute for Silicate Research and Mr. J. Patrick Nicholson of N-Viro Energy Systems for sharing some of their findings on kiln dust research.

The authors are grateful to Valley Forge Laboratories' staff members for performing the physical testing and to the staff and support personnel of Trow, Ltd. for performing all characterization testing as project subconsultant.

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the U.S. Department of Energy or The Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

EXECUTIVE SUMMARY

An 18-month laboratory investigation was conducted in order to determine the effectiveness of substituting kiln dusts for hydrated lime in lime-fly ash-aggregate road base systems. This investigation was co-sponsored by the U.S. Department of Energy and the U.S. Department of Transportation-Federal Highway Administration as the first part of a two-phased program designed to evaluate the characteristics and performance of kiln dusts and fly ashes. The second part of the program will involve a series of field demonstration projects.

Background Information

From 20 to 24 million tons per year of kiln dusts are generated during the production of lime or Portland cement. Of this total, 18 to 20 million tons are cement kiln dust, with from 2 to 4 million more tons of lime kiln dust. These dusts are collected by cyclones, electrostatic precipitators, and baghouses. Cyclones or multi-clones are primary collection systems used to collect coarser size particles. Electrostatic precipitators and baghouses are more highly efficient and are usually divided into compartments or stages, with the first compartments capturing the relatively coarse particles and the last compartments collecting the finer size particles. In most systems, it is possible to separate the dust collected from different compartments within the system.

At many cement plants, dust from one or more of the forward compartments is returned to the kiln, while the remaining dust, usually from the rear compartments, is either disposed of or utilized in some way. Comparatively little of the dust produced by the lime industry is recycled or utilized. The principal difference between various sources of lime kiln dust is the type of limestone burned in the kiln, either high calcium or dolomitic limestone.

In addition to fresh kiln dusts, there are well in excess of 100 million tons of kiln dust in stockpiles. Most of this stockpiled material has been in place for a number of years, is highly weathered, and may even be contaminated with other material. However, it is possible to condition kiln dusts for a comparatively short period of time (perhaps up to several months) and still utilize the conditioned material.

Research Approach

The following work tasks were performed during the laboratory investigation:

- Task A - Select Materials for Laboratory Testing
- Task B - Characterize Kiln Dusts and Fly Ashes and Establish Optimum Kiln Dust-Fly Ash Proportions
- Task C - Establish Optimum Mix Proportions for Kiln Dust-Fly Ash-Aggregate Systems

- Task D - Evaluate Engineering Properties of Kiln Dust-Fly Ash-Aggregate Systems.

Selection of Materials

A total of 45 kiln dust samples were selected for inclusion in the testing program, including 33 cement kiln dust samples and 12 lime kiln dust samples. Of the 33 cement dust samples, 17 were from wet process plants and 16 were from dry process plants. Of the 12 lime dust samples, 7 were from plants burning high calcium limestone and 5 were from plants burning dolomitic limestone. Included in the 45 dust samples were 4 stockpiled samples, 3 from cement plants and 1 from a lime producer.

All fresh kiln dust samples were obtained by cement or lime company personnel using a standard procedure to provide 136.2 kilograms (or 300 pounds) of a composite sample taken in equal daily sampling increments at random times over a 15-day period of normal kiln operation. This resulted in relatively consistent samples.

A total of 18 fly ash samples were provided by ash marketing organizations or utility companies from 15 states. Included in these samples were 12 Class F fly ashes from the burning of bituminous coal; 5 Class C fly ashes from the burning of sub-bituminous or lignite coal; and one fly ash from the burning of a blend of bituminous and sub-bituminous coals.

Six aggregate samples were also obtained. These included a dolomitic limestone, a calcitic limestone, a granitic gneiss, a siliceous sand and gravel, a river sand, and an air-cooled blast furnace slag. With the exception of the river sand, the aggregate samples were graded according to general requirements of base course materials.

Characterization of Kiln Dust and Fly Ash Samples

The characterization testing of kiln dusts and fly ashes involved four main aspects:

1. Physical properties (particle size distribution, specific gravity, Blaine fineness, and pH).
2. Chemical properties (major oxides, loss on ignition, carbon and carbon dioxide.
3. Mineralogical composition (major minerals and free lime).
4. Pozzolanic/hydraulic indices (mortar cube strengths for accelerated and ambient curing conditions).

Key physical characteristics of kiln dusts are their particle size and Blaine fineness. The main chemical components of kiln dusts are calcium oxides, alkalies, sulfates, and loss on ignition. The higher the loss on ignition, the more carbonate is present and the less calcium oxides or silicates are available for reaction. Free lime is the single most important mineralogical constituent, although residual cementitious compounds (silicates and aluminates) in cement kiln dusts should also be considered. Accelerated 7-day cube strengths provide an indication of hydraulic reactivity.

Classification of Kiln Dusts

The most suitable means of classifying cement kiln dusts are the kiln process and the degree of separation in the dust collection system. Four groups of cement kiln dust are:

Group I - Dry Process - Total Collection
Group II - Dry Process - Separation
Group III - Wet Process - Total Collection
Group IV - Wet Process - Separation.

The major difference between lime dusts is reactivity, which is most directly related to free calcium (or magnesium) oxide. A simple temperature rise test was performed as a measure of lime kiln dust reactivity. A temperature rise of 20°C. (68°F.) was selected as the criteria for reactivity. Two groups of lime kiln dust are:

Group H - Moderately to Highly Reactive (above 20°C.)
Group L - Slightly Reactive (below 20°C.).

The hydration or slaking of the free lime in Group H dusts converts the reactive CaO to calcium hydroxide and is accompanied by considerable heat release.

Determination of Optimum Kiln Dust-Fly Ash Ratios

Optimum ratios for kiln dust-fly ash combinations were determined on the basis of the strength development of test cylinders. Test specimens in this phase of the program were prepared in a Carver laboratory press mold, using a standard molding procedure.

Kiln dust-fly ash control mixes were prepared with a typical Class F bituminous coal fly ash (FA-16). These were compared with a control mix consisting of one part by weight commercial high calcium hydrated lime and four parts by weight of the same fly ash. Only 11 of the 45 kiln dusts exhibited lower 7-day strengths than the lime-fly ash control mix. Similar control mixes were prepared in which 76 percent by weight of each test sample consisted of Ottawa sand, with the kiln dust-fly ash proportions remaining the same. The kiln dust-fly ash mixes were compared with a similar control mix using the same aggregate percentage and a 1:4 ratio of lime to fly ash. This time, only 8 of the 45 kiln dust-fly ash mixes were lower in 7-day strength than the lime-fly ash sand control mix.

A total of 66 kiln dust-fly ash test mixes were prepared using at least three different kiln dust-fly ash ratios for each test mix. Most of the cement dust-fly ash mixes had an optimum kiln dust-fly ash ratio of 1:1. Optimum strength for the lime dust-fly ash mixes occurred almost equally at 1:1 and 1:2 kiln dust-fly ash ratios.

The use of Class C fly ash results in much higher levels of initial strength than Class F fly ash. Users of Class C fly ash should be cautioned that special handling procedures, such as conditioning and stockpiling, may be necessary prior to use. Placement and compaction of mixes containing Class C fly ash should be done as soon as possible after mixing.

Kiln Dust-Fly Ash-Aggregate Strength Development

A total of 24 fresh kiln dust samples (18 cement dusts and 6 lime dusts) and four stockpiled dusts were chosen for analysis of kiln dust-fly ash mix combinations with aggregate. All six aggregates and 11 of the 18 fly ashes were also included.

The same kiln dust-fly ash combinations evaluated in the previous phase of the testing were analyzed in combination with different aggregates. At least two aggregate types, limestone and siliceous, were tested for every mix combination. The levels of aggregate used were 76 and 82 percent by dry weight of mix. Three or more kiln dust-fly ash ratios were investigated for each mix combination. Triplicate samples were prepared for 7-day curing at 23°C. (73°F.) and 38°C. (100°F.). All specimens were molded and compacted in accordance with ASTM C593 requirements at optimum moisture conditions.

A total of 36 control mixes were tested, including 12 conventional lime-fly ash-aggregate mixes and 24 kiln dust-fly ash-aggregate mixes. The type of aggregate is influential in strength development, since only 3 of the 6 aggregates used in control mixes equalled or exceeded the ASTM C593 minimum strength requirement. The kiln dust-fly ash-aggregate control mixes were all prepared with the same fly ash (FA-16) and aggregate (granitic gneiss) to compare the strength gain potential of each dust. Of the 24 fresh dusts tested, only one cement kiln dust and one lime kiln dust sample could not meet or exceed the ASTM C593 minimum strength requirement.

A total of 64 kiln dust-fly ash-aggregate mix combinations were also tested. The most consistently high strength development was observed with the Type I (dry total) dusts, followed by Type III (wet total) dusts. The Type II (dry separated) and Type IV (wet separated) dust mixes consistently had the poorest strength development. A majority of kiln dust-fly ash-aggregate mixes developed 7-day compressive strengths equal to in excess of the strengths obtained from comparable lime-fly ash-aggregate mixes. The 7-day strength development of kiln dust-fly ash-aggregate mixes containing Class C fly ash was considerably higher than that of similar mixes containing Class F fly ash.

When using cement kiln dusts, there is a strong indication that the 7-day compressive strength of kiln dust-fly ash-aggregate mixes is related to the level of reactive oxides present in the cement kiln dust. The reactive oxides are determined by the following equation:

$$\text{Reactive Oxides} = [(CaO + MgO) - LOI] + \text{Alkalis } (Na_2O + K_2O)$$

where the value of the alkalis is limited to a maximum of 6.

There is no direct correlation between free lime content or level of reactive oxides with the 7-day compressive strength of kiln dust-fly ash-aggregate mixes containing lime kiln dusts. Special handling procedures, including an excess of slaking water during mixing, are necessary with the use of reactive (Group H) lime dusts.

Kiln Dust-Fly Ash-Aggregate Engineering Properties

The long-term strength development of kiln dust-fly ash-aggregate compositions is similar to that of lime-fly ash-aggregate. The kiln dust-fly ash-aggregate mixes definitely gain strength with age and many such combinations are capable of developing very high compressive strengths. Although the early strengths of mixes with Class C fly ash are usually higher than those with Class F fly ash, their long term strengths (90 days or more) are often comparable.

Most kiln dust-fly ash-aggregate compositions are dimensionally stable over extended periods, regardless of whether samples were submerged or cured in a moist room. Volume changes were usually negligible or comparable in magnitude to conventional lime-fly ash-aggregate compositions. Possible exceptions are mixtures in which cement dust with a high sulfate content (10 percent or greater) or reactive lime dust with a high free lime content (20 percent or greater) are used in the mix. Test specimens containing these types of kiln dust did exhibit considerable volumetric expansion. Extreme caution is advised if considering using any high sulfate cement kiln dust or any lime stack dust with a high free lime content.

Kiln dust-fly ash-aggregate test mixes showed excellent freeze-thaw durability, except for two mixes in which a high sulfate, high alkali cement kiln dust sample was used. As a general rule, cement kiln dusts having a sulfate content equal to or greater than 10 percent should not be considered or should be used with the utmost caution in a pozzolanic base system. Except for high sulfate cement dusts, the use of kiln dust with fly ash and aggregate produces extremely durable compositions which are quite comparable to lime-fly ash-aggregate mixes.

Based on data developed from this study, it is evident that most kiln dusts sampled and tested during this research program can be successfully substituted for hydrated lime in conventional lime-fly ash-aggregate road base systems. The ratio of kiln dust to fly ash is usually in the 1:1 to 2:1 range, compared to a normal lime to fly ash ratio of 1:4. A majority of the kiln dust-fly ash-aggregate mixes tested developed high 7-day compressive strengths. Because of higher early strength, it may be possible to extend the normal construction season when using kiln dust-fly ash-aggregate mixes. Since each source of kiln dust is different, a complete testing program is recommended in order to determine optimum mix proportions and construction cutoff dates.

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

1. PURPOSE OF STUDY

The objective of this research, which is co-sponsored by the U.S. Department of Energy and the U.S. Department of Transportation-Federal Highway Administration, is to determine the effectiveness of substituting kiln dusts from cement or lime production in place of hydrated lime in lime-fly ash-aggregate road base systems.

The combined Department of Energy-Federal Highway Administration program is a two-phased research investigation. The initial phase, described in this report, is an 18-month laboratory study designed to evaluate a spectrum of kiln dusts and fly ashes. The results of this phase of the program are presented in this report and will be used as the basis for the second phase, which will involve a series of field demonstration projects. These projects will be conducted in at least three different states located in various regions of the country and will utilize materials combined in accordance with mix design recommendations developed in this phase of the program.

2. BACKGROUND INFORMATION

The manufacture of lime and cement are among the nation's most energy-intensive industrial processes. These manufacturing processes not only require significant quantities of fuel, but also generate relatively large amounts of fugitive dust emissions. These dusts represent a high initial input of energy and often possess some of the characteristics of the cement or lime raw feed materials. Consequently, they may constitute a prospective source of raw material and, depending upon their composition, may also have a number of potentially useful applications. This report discusses the generation, collection, distribution, and use of cement and lime kiln dusts, with particular emphasis on utilization prospects as a highway road base construction material.

2.1 Generation and Collection of Kiln Dusts

The majority of dust generated by the making of portland cement or hydrated lime is produced from the operation of kilns. Kilns are large, cylindrical, rotating, inclined metal tubes, usually ranging from 8 to as much as 18 feet in diameter and from 150 up to 500 feet in length. Typically, length to diameter ratios range from 30:1 to 40:1. At the lower end of the kiln is the fuel burning section (fired by pulverized coal, gas, or oil), in which the temperature of the flame may be as high as 1815°C. (3300°F.). Raw materials are fed into the upper end of the kiln and move down the kiln toward the burner as the kiln rotates. As the raw materials are heated and tumbled in the kiln, dust particles are created and are carried with the exit gases out the upper end of the kiln. These gases are cooled and the accompanying dust particles are captured by efficient dust collection systems.

2.1.1 Production of Portland Cement

Raw materials used in the production of portland cement contain four particular compounds: lime, silica, alumina, and iron oxide. Various combinations of limestone, shale, clay, sand, cement rock, marl, iron ore, or other materials are used. These materials are ground together, usually to 200 mesh or finer, and, after blending, are ready for introduction to the kiln.

The blended and ground raw materials may be added to the kiln either as a dry mixture or as a water slurry. The wet process of cement manufacture differs from the dry process only insofar as the raw materials are ground and burned wet. In the wet process, water is added to the raw materials after crushing and prior to grinding. In the dry process, the raw materials are crushed, fed into a dryer, and then pulverized to a fine powder consistency.

On entering the kiln, the raw materials (either wet or dry) undergo two important series of chemical reactions:

1. Decomposition of carbonates of lime and magnesia into the oxides of these two materials.

2. Recombination of these oxides with silica and alumina to form the three essential compounds of Portland cement:tricalcium silicate, dicalcium silicate, and tricalcium aluminate.

In the dry process kiln, about 25 percent of the kiln length is used to heat the raw materials; 50 percent is utilized to drive off carbon dioxide, and 25 percent constitutes the clinkering zone. In a wet process kiln, a somewhat greater percentage of the kiln length is required in the first zone due to drying of the raw feed. (1)

2.1.2 Production of Lime

Lime, in the form of quicklime, is produced from crushed limestone (either high calcium or dolomite) by calcination in a kiln. Almost 90 percent of present lime production in the United States comes from rotary kilns, which also produce the highest quality and most uniform lime product. Limestone begins to decompose significantly at 900°C. (1,650°F.). Dolomite begins to decompose at approximately 600 to 700°C. (1110 to 1290°F.). Calcining temperatures can vary over a fairly wide range, depending on the kiln type, desired lime product, and type of fuel used. Rotary kilns usually operate at temperatures between 1,120 and 1,320°C. (2,050 and 2,400°F.). Hard burned or dead burned lime products require kiln temperatures between 1,538 and 1,650°C. (2,800 and 3,000°F.). (2)

Other kiln types in use in this country are the vertical or shaft kiln, the fluo-solids or fluidizing kiln, and the calcimatic or circular refractory kiln. Generally, these kilns do not generate as much dust as a rotary kiln. It has been estimated that vertical kilns generate only 2 to 5 percent as much dust per ton of lime as rotary kilns. (2)

2.1.3 Dust Collection

The amounts and characteristics of by-product dusts removed from the exhaust gases at cement and lime plants depend on a number of factors. The most influential of these factors are the characteristics of the raw feed materials, kiln design and operation, fuel type, and the design of the dust collection system. The nature of the finished product is a further consideration having some effect on dust characteristics. In cement manufacture, the type of cement being produced may cause the source and proportioning of raw materials to change, modifying the kiln dust composition. In the manufacture of lime, the major variable having an impact on the chemistry of the resultant kiln dust involves the use of calcitic or dolomitic limestone feed.

The devices most commonly used for collection of dust particulate emissions from cement and lime kilns are:

- Cyclones
- Electrostatic precipitators
- Baghouses.

In order to provide a basic understanding of these devices, the operating principles of each are briefly discussed.

Multiple cyclones are often used as the sole dust collection equipment for small capacity vertical lime kilns. For rotary lime or cement kilns, the peak collection efficiency of cyclonic systems range from 92 to 95 percent, which is inadequate to meet current strict particulate emission standards. Coarser size dust particles from the gas stream are settled first by centrifugal force in low velocity gas flow. As the velocity of the gas stream is accelerated in the multiple cyclones, operating in parallel as a composite unit, some of the finer dust particles are also separated. The dust particles so collected settle into a chamber at the bottom of the cyclone apparatus. In many lime and cement plants, multiple cyclones (sometimes referred to as multi-clones) are used as the primary collector to complement more efficient collection systems and provide a pre-cleaned exhaust gas.

Electrostatic precipitators are widely used for dust collection in the cement industry, as well as for the collection of fly ash from the burning of pulverized coal at electrical utility plants. They are normally capable of collection efficiencies of 99 percent or higher. Electrostatic precipitators operate by inducing an electrical charge in the area through which flue gases flow and providing oppositely charged collection plates to attract the charged particles in the gas stream. These particles are attracted to and accumulate on the collection plates. At intervals, the electric current to the collection plates is interrupted and the dust particles are dislodged by means of hammers. The dust particles then fall into hoppers and from there are conveyed to collection silos by means of screws, slides, or gates. Most precipitators are divided into compartments or stages and the dust collected in different stages can be separated.

Baghouses are structures containing a large number of fiberglass or cloth bags with a very fine mesh texture. Baghouses are multiple modular compartments with the capability of separating dust from different compartments. Exhaust gases are sometimes cooled to a temperature of 260 to 371°C. (500 to 700°F.) in order to not damage the bag fabric. The gases pass through the baghouse by means of either forced draft or induced draft fans and the dust particles are captured in the mesh of the collection bags. The collected dust is periodically dislodged from the surface of the bags by a shaking mechanism. The dust drops into a large V-shaped hopper and is discharged to a collection silo as described earlier. Baghouses reportedly achieve the highest consistent collection efficiency of all dust control systems, sometimes approaching 99.9 percent efficiency. (2)

In addition to the above mentioned systems, some lime plants also use wet scrubbers, which are highly efficient but produce a dust-laden slurry. Some lime plants use a dry scrubber system, employing a fine mist instead of a spray as in wet scrubbing. Another system in use at a few lime plants is the gravel bed filter, consisting of multiple interconnected filter modules, each containing gravel particles in a horizontal bed. Dust is removed from the filter by back flushing with air.

Rotary kilns have a large surface area and lose considerable amounts of heat by radiation to the ambient air. To achieve improved thermal efficiency, together with increased kiln capacity, a number of lime plants and dry process cement plants employ preheater devices. These are of two basic types (shaft or traveling grate), with the shaft type being the more efficient. Preheaters employ a moving bed of granular feed solids which interact with the hot kiln exit gases to elevate the temperature of the kiln feed materials and, in some cases, achieve partial calcination prior to their entry in the kiln. Although considerable fuel savings have been documented using preheaters, some stones are too soft or decrepitate too readily for them to be handled in a preheater without the formation of excessive dust. In the cement industry, suspension type preheaters are operated with partial bypass in order to reduce alkali circulation. (3)

2.2 Kiln Dust Production-Quantities and Locations

The annual production of portland cement in the United States is between 75 and 80 million tons. There are presently 163 operating cement plants in 41 states. (4) Lime production is approximately 20 million tons, produced at 87 commercial lime plants and 75 captive lime plants in 30 states. (5)

At this time, it is estimated that the total annual combined production of cement and lime kiln dusts ranges from 20 to 22 million tons per year. Of this total, 18 to 20 million tons are cement kiln dust, with approximately 2 million tons of lime kiln dust.

In the cement industry, the amount of dust generated represents from 10 to 20 percent of the raw material used in cement manufacture. Many producers utilize all or a fraction of the dust produced at their plant as recycled raw material where alkali levels of the dust are sufficiently low to permit reuse in the kiln. Recycling of cement kiln dust may involve separation of the dust from one or more compartments within the dust collection system, or the collection of the entire dust output from the system and its partial or total reintroduction into the kiln. Therefore, cement kiln dust collection involves either the total dust capture or the separation of some portion of the dust from forward compartments (those closest to the kiln) for the purpose of recycling. Previous estimates indicate that approximately 6 to 10 million tons of cement kiln dust are either recycled or utilized in some way, (6) resulting in approximately 8 to 12 million tons of waste cement dust annually.

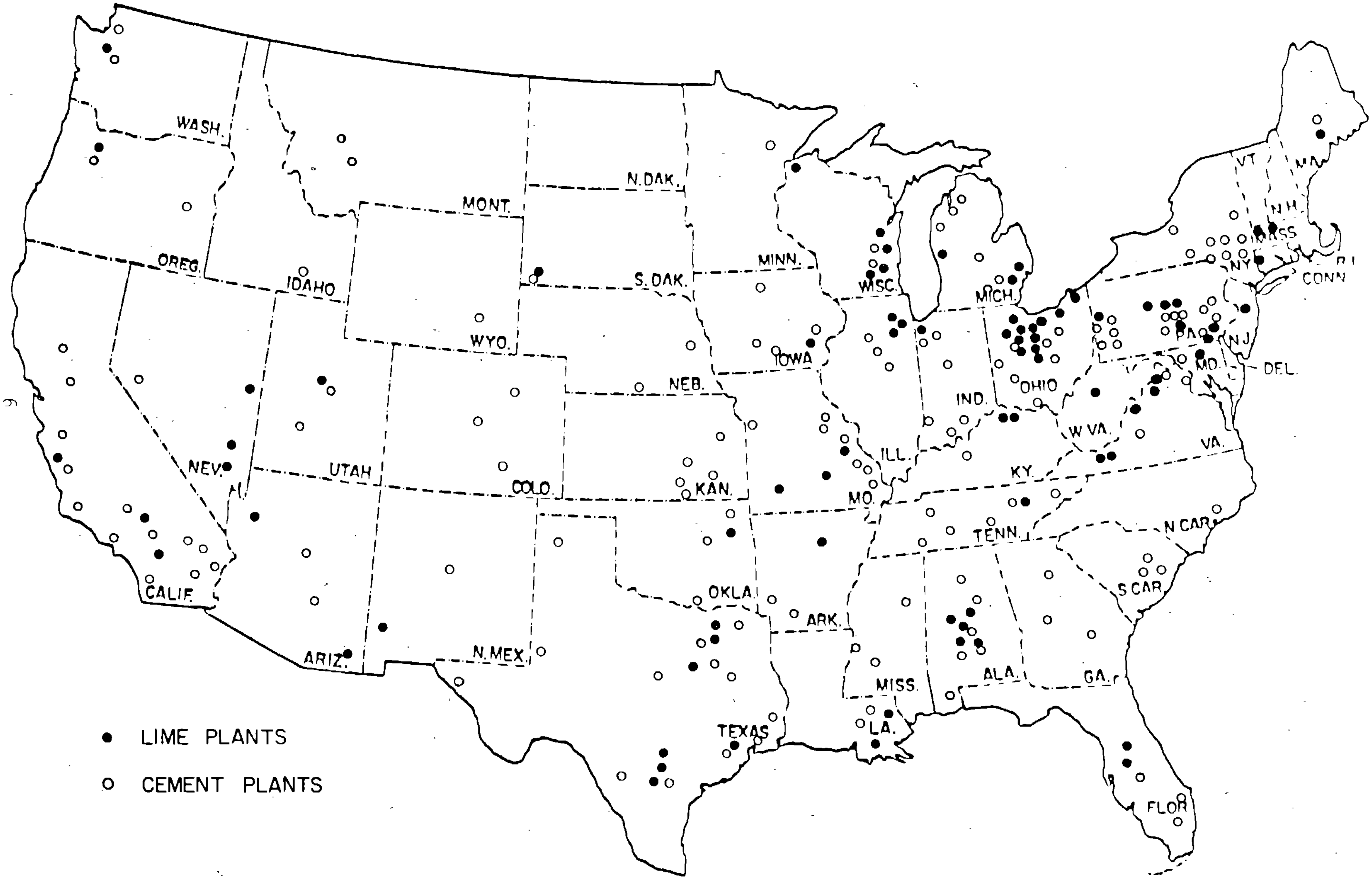
In the lime industry, kiln dust generation has been found to average approximately 76 tons per day per plant, or in excess of 1.8 million tons per year. Over 75 percent of this dust is disposed of due to lack of readily available markets. (7) Since very little dust is generated by vertical kiln plants, the overwhelming majority of lime kiln dust is produced by rotary kiln operations. (8) There is at this time little or no separation or recycling of kiln dust within the lime industry.

In addition to freshly produced kiln dusts, there are many large stockpiles of kiln dust throughout the country. Accumulations in these stockpiles have been estimated to be well in excess of 100 million tons. These waste heaps not only pollute the environment, but the aging or weathering process results in contamination and diminished reactivity, further decreasing the potential for recycling of the material in these stockpiles.

Figure 1 shows the locations of all operating cement and lime plants in the United States. Of the 163 cement plants, over half are located in eight

FIGURE I

LOCATIONS OF CEMENT AND LIME PLANTS



states (Alabama, California, Indiana, Michigan, Ohio, Pennsylvania, Tennessee, and Texas). Other states having a concentration of cement producing operations are Kansas, Missouri, and New York. There are 61 commercial lime plants in 30 states which have rotary kilns. Based on the location of these rotary kiln facilities, the states which appear to have the most available lime kiln dust are Alabama, Illinois, Michigan, Missouri, Ohio, Pennsylvania, Texas and Virginia.(9) The major lime and cement producing states were primary choices during the selection of kiln dust samples for testing.

2.3 Applications for Kiln Dusts

Although substantial quantities of cement and lime kiln dusts must be disposed of each year, there is, nevertheless, a wide range of current and potential uses for these materials. In the cement industry, the ideal use is to recycle the kiln dusts back into the production cycle, wherever possible. Therefore, at many cement plants where alkali levels permit, all or some portion of the kiln dust is returned to the kiln by insufflation or combined with the raw feed.

Certain lime kiln dusts, because of high available lime content, are very reactive in water and may be considered as possible replacements for hydrated lime in certain applications.

A comprehensive review of the disposal and utilization of cement kiln dusts was conducted by Davis and Hooks.(10) Many of the uses outlined in this report are also applicable to lime kiln dusts. The range of potential and actual markets for kiln dusts include:

- Agricultural uses
- Waste stabilization
- Filler materials
- Highway construction

2.3.1 Pozzolanic Road Base Materials

One of the most promising applications for the use of kiln dusts in highway construction is in pozzolanic road base compositions, involving some form of lime-fly ash stabilization. These compositions are usually mixtures of commercial hydrated lime, fly ash, and aggregate, combined with water in the proper proportions and compacted to form a dense, stable mass. In some cases, portland cement is added to or used in place of hydrated lime in pozzolanic pavements.

A pozzolan is defined as "a siliceous or aluminous and siliceous material which is in itself chemically inert, and possesses little or no cementitious value, but, when in a finely divided form and in the presence of water, will react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." (11)

The most commonly available pozzolan in use in the United States is fly ash. Fly ash is the fine-grained particulate matter resulting from the combustion of pulverized or powdered coal at utility power plants. Fly ash is recovered from boiler flue gases by means of electrostatic precipitators or mechanical collection systems. It is estimated that between 50 to 60 million tons of fly ash are collected annually at a total of 402 coal-burning power plants located in 41 states. By 1990, it has been projected that over 100 million tons of fly ash will be produced annually.(12)

The locations of all existing coal-fired power plants in the United States are shown in Figure 2. From this map, it is evident that there is a concentration of plants along the Ohio River and the Great Lakes. The six largest ash-producing states are Ohio, Pennsylvania, Illinois, Indiana, Kentucky, and West Virginia. The fly ash collected annually in these six states is nearly half of all the fly ash generated each year throughout the entire United States.

Because kiln dusts contain some calcium oxide or unreacted lime, they may be used in place of hydrated lime or Portland cement as a pozzolanic road base material. Recognizing this, patents have been issued by the U.S. Patent Office for the use of cement kiln dust and lime kiln dust as a component of pozzolanic base course compositions. (14, 15) As of this time, at least thirty test sections have been placed in seven different states to investigate the field performance of kiln dust-fly ash-aggregate base mixtures. (16)

2.3.2 Nature of Pozzolanic Reactions

The reactions that occur in the lime-fly ash-water system to form cementitious compounds are complex. According to Minnick (17), these reactions involve various combinations of hydrated calcium and/or magnesium with amorphous (glassy) silica and/or alumina in the presence of water to form tobermorite (calcium or magnesium silicate hydrates), ettringite (tricalcium aluminate trisulfate), and the low-sulfate form of sulfoaluminate (tricalcium aluminate sulfate). The following equations are indicative of the possible reactions that may occur in a pozzolanic system:

$$RO \xrightarrow{H_2O} R(OH)_2$$

$$RO \xrightarrow{H_2O\cdot CO_2} RCO_3 + H_2O$$

$$R(OH)_2 \xrightarrow{CO_2} RCO_3 + H_2O$$

$$R(OH)_2 + SiO_2 \xrightarrow{H_2O} x\ RO\cdot ySiO_2\ zH_2O$$

$$R(OH)_2 + Al_2O_3 \xrightarrow{H_2O} x\ RO\cdot yAl_2O_3\cdot zH_2O$$

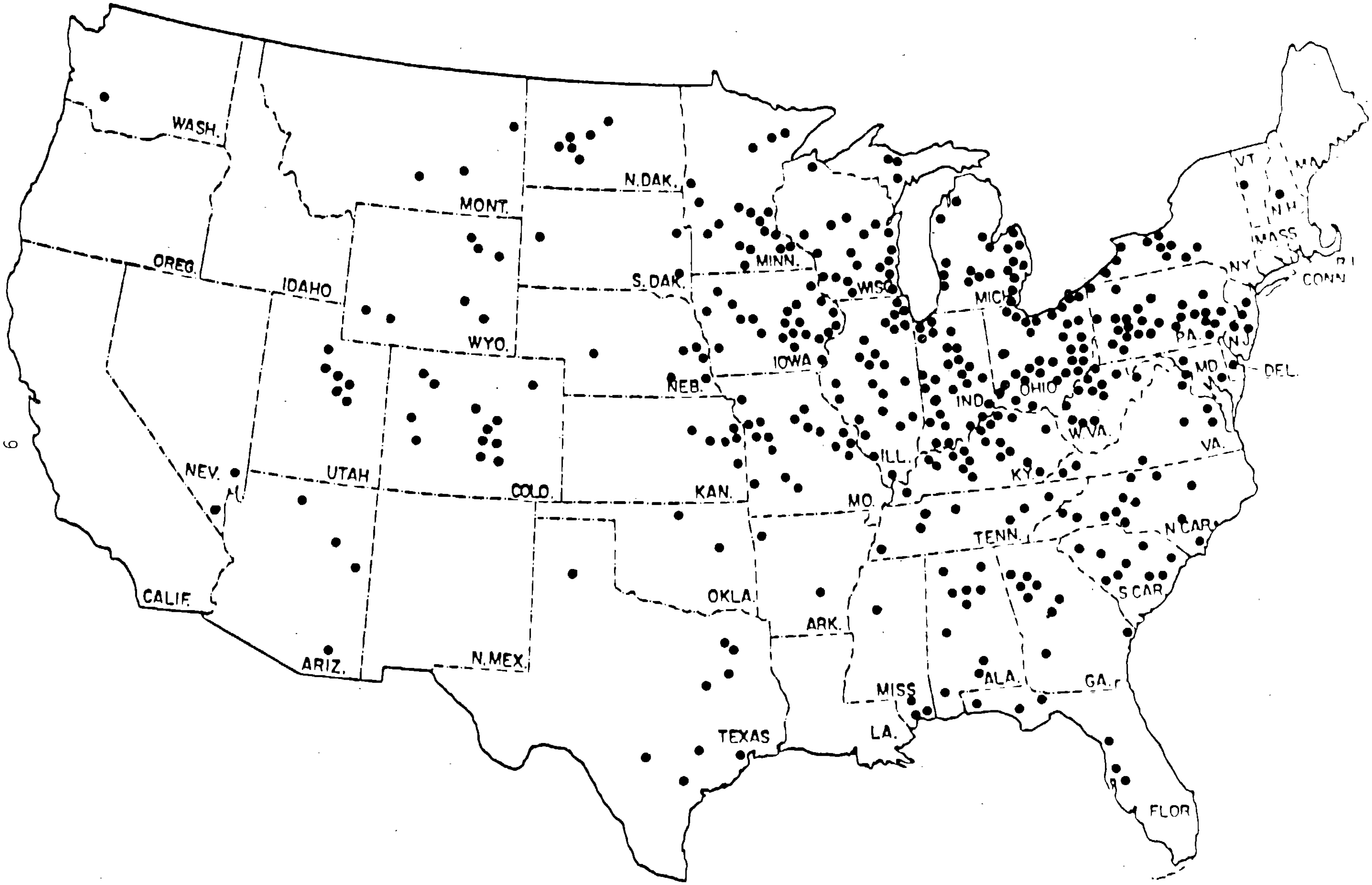
$$R(OH)_2 + Al_2O_3 + SiO_2 \xrightarrow{H_2O} x\ RO\cdot yAl_2O_3\ zSiO_2\ wH_2O$$

$$R(OH)_2 + SO_3 + Al_2O_3 \xrightarrow{H_2O} X\ RO\cdot yAl_2O_3\cdot zSO_4\ wH_2O$$

where R represents either calcium (Ca^{++}) or magnesium (Mg^{++}) or combinations of these ions.

FIGURE 2

LOCATION OF COAL BURNING POWER PLANTS



The amorphous glassy materials in fly ash are the constituents that react to form complex silicates and aluminates. The strength developed as a result of the pozzolanic reaction depends on the quantity of cementitious materials produced, which is influenced by the ability of the silica in the system to enter into solution. Essentially, the crystalline or quartz form of silica is insoluble within the normal range of temperatures, so that only the amorphous or glassy silica is able to enter into the pozzolanic reaction.

In the silica-calcium hydroxide-water system, the effect of the calcium hydroxide on the pH of the solution must be considered. The pH has little effect on the solubility of the silica below a pH of approximately 9, but, as the solution becomes more basic, the solubility increases rapidly with increasing alkalinity.(18) The rate of solubility of the silica is also influenced by its particle size, surface area, and bound water content. It has been noted that when a significant quantity of lime is added, the pH of the mixture is elevated to approximately 12.4, which is the pH of saturated lime water.(19)

The type of lime has an effect on the pozzolanic reaction. If high calcium quicklime is used, the calcium oxide will convert to calcium hydroxide and will react the same as calcium oxide, except for the added heat of hydration and the additional reactive constituents. The presence of magnesium oxides and hydroxides in dolomitic lime results in an even more complex pozzolanic reaction mechanism.(20)

The pozzolanic reactivities of different fly ashes are quite variable. The following factors are indicative of good pozzolanic reactivity:

- A fairly high percentage of fly ash particles passing the No. 325 (45 micron) sieve or relatively high surface area.
- Increased SiO_2, $SiO_2 + Al_2O_3$, or $SiO_2 + Al_2O_3 + Fe_2O_3$
- Low carbon content or loss on ignition.
- Increased alkali contents.(21).

A wide variety of aggregates have been used to produce pozzolanic stabilized base materials. Well-graded aggregates usually require the least amount of total lime and fly ash for effective stabilization, while poorly graded aggregates normally require more lime and fly ash than rounded aggregates. Generally, the lime and fly ash constitute about 15 percent by weight of the total mixture, with the ratio of lime to fly ash in the range of 1:3 to 1:4. Also, the moisture content of the mixture should be sufficient for the pozzolanic reactions to occur and should also produce the highest possible density at a given compactive effort.(22)

2.3.3 Nature of Portland Cement Hydration Reactions

Hydration of calcium silicates plays an essential role in the hardening of Portland cement. Two calcium silicates, tricalcium silicate (C_3S) and dicalcium silicate (C_2S) constitute about 75 percent by weight of Portland cement, with tricalcium silicate (C_3S) being the most predominant. In their hydration reactions, both of these silicates produce a calcium silicate hydrate referred to as tobermorite gel, which is the major component in the setting and hardening of Portland cement paste. In the hydration reaction, C_2S reacts much more slowly with water than does C_3S. Neither of these calcium silicates is a pure compound, each possibly containing small amounts of Al_2O_3, MgO, or other impurities. Therefore, the tobermorite gel involves a series of hydrates having continuously varying compositions.

The cementing properties of tobermorite gel are caused by ionic forces residing in the surfaces of the constituent materials. The magnitudes of these forces depend on the nature and extent of the surfaces involved. Thus, the composition and specific surface area are two of the most important properties of the tobermorite gel.(23)

The factors most influential in affecting the hydration of Portland cement are:

- The presence of uncombined CaO and $Ca(OH)_2$ in hydrated and unhydrated calcium silicates and whether the $Ca(OH)_2$ is in a crystalline or amorphous form.
- The CaO/SiO_2 ratio in the tobermorite gel, which depends on the concentration of lime in solution.
- The water of hydration or H_2O/SiO_2 ratio in the tobermorite gel.
- The specific surface area of the tobermorite gel. (23)

In addition to the formation of tobermorite gel, the hydration of Portland cement also involves the formation of various crystalline forms of calcium aluminate hydrates from tricalcium aluminate (C_3A). At least four or five different calcium aluminate hydrate compounds may be formed during the hydration of portland cement. Each of these compounds assumes a unique crystalline form involving a different amount of hydrate. Other calcium aluminate hydrate compounds involved in cement chemistry contain varying amounts of either sulfate, carbonate, alkali, or chloride anions.

Introduction of fly ash to cementitious reactions is advantageous, insofar as the silica and alumina in the fly ash are free to react with liberated calcium oxide (CaO) from the hydration of portland cement as a pozzolanic reaction. The American Society for Testing and Materials (ASTM) divides fly ash into two distinct classes: Class F and Class C. Class F fly ash results from the burning of anthracite or bituminous coal, while Class C fly ash results from the burning of lignite or sub-bituminous coal. (24) In essence, Class F fly ashes are "low lime" ashes with a CaO content usually less than 5 percent, while Class C fly ashes are "high lime" ashes with a CaO content up to 30 percent. Most of the CaO in "high lime" fly ashes is present in a combined state with silicates and aluminates and is not free to react with other constituents. Although the amount of free lime (or uncombined CaO) is generally less than 2 percent in most Class C fly ashes, many of these "high lime" ashes are hydraulic as well as pozzolanic and develop strength rapidly when mixed with water. (25)

3. RESEARCH APPROACH

To accomplish the contract objective, the following tasks were performed in this study:

1. Task A - Select Materials for Laboratory Testing.
2. Task B - Characterize Materials and Establish Optimum Kiln Dust-Fly Ash Properties.
3. Task C - Establish Optimum Mix Proportions for Kiln Dust-Fly Ash-Aggregate Systems.
4. Task D - Evaluate Engineering Properties of Kiln Dust-Fly Ash-Aggregate Systems.

Throughout much of the program, these tasks were carried out independently, although at times two or more work tasks were performed concurrently, particularly in those instances where a number of material samples were delivered at different times than others. In general, the information developed or results obtained in each task affected the procedures to be employed in successive tasks.

The following paragraphs discuss briefly the basic approach employed in each of the previously mentioned work tasks. Other sections of this report present a more comprehensive description of the work performed and the test results obtained in each of the work tasks.

3.1 Task A - Select Materials for Laboratory Testing

A total of 45 samples of kiln dust representing typical by-products from the manufacture of Portland cement and hydrated lime were selected for testing. These samples were representative of various operating conditions affecting dust composition and reactivity, such as kiln type, raw feed variations, dust collection techniques, and handling or disposal practices.

In addition to kiln dust, 18 samples of fly ash were also obtained, representing a variety of ash products that are available throughout the United States. Factors that were considered in the selection of fly ash samples included type of coal, coal source, and power plant location.

Aggregate materials, representative of a number of basic aggregate types, were also included in the sampling program. Aggregate samples selected were representative of calcareous, siliceous, and granitic rock types, as well as a blast furnace slag material.

3.2 Task B - Characterize Kiln Dusts and Establish Optimum Kiln Dust-Fly Ash Proportions

In this task, laboratory analyses were performed on representative fractions of each kiln dust and fly ash sample to identify physical, chemical, and mineralogical properties considered suitable for prediction of reactivity. Based on characterization test results, selected kiln dust and fly ash samples were combined in order to establish optimum kiln dust-fly ash proportions on the basis of strength development.

A series of control mixtures were prepared and tested to evaluate the relative strength of different kiln dusts. Test specimens for each kiln dust sample were molded which contained the kiln dust in one of the following conditions:

- As kiln dust alone
- Blended with a typical Class F fly ash
- Blended with Ottawa sand and a typical Class F fly ash.

Each kiln dust was also combined with one or more fly ashes located within a reasonable distance in the same geographical region to prepare specimens for compressive strength testing. The strength values from all kiln dust-fly ash combinations were evaluated and used to select representative kiln dust and fly ash samples for testing in combination with different aggregates in the next phase of the test program.

3.3 Task C - Establish Optimum Mixture Proportions for Kiln Dust-Fly Ash-Aggregate Systems

Selected kiln dust and fly ash samples from the previous work task were combined with different aggregates in various mix proportions in order to evaluate the 7-day, 100°F. (38°C.) strength development of each test mix in terms of:

- Kiln dust-fly ash ratio
- Percentage of aggregate in the mix
- Type of aggregate
- Curing conditions.

The compressive strength of all test mixes was determined. Control mixes were also prepared and tested for strength development. The strength values of all mixes were evaluated and used to select optimum formulations from a number of material combinations for testing in the final phase of the program.

3.4 Task D - Evaluate Engineering Properties of Kiln Dust-Fly Ash Aggregate Systems

The optimum strength proportions from the kiln dust-fly ash-aggregate combinations chosen in the previous task were further analyzed to determine other engineering properties such as:

- Moisture-density characteristics
- Long-term compressive strength
- Durability
- Volume Stability

- Autogenous healing.
- Resilient modulus.

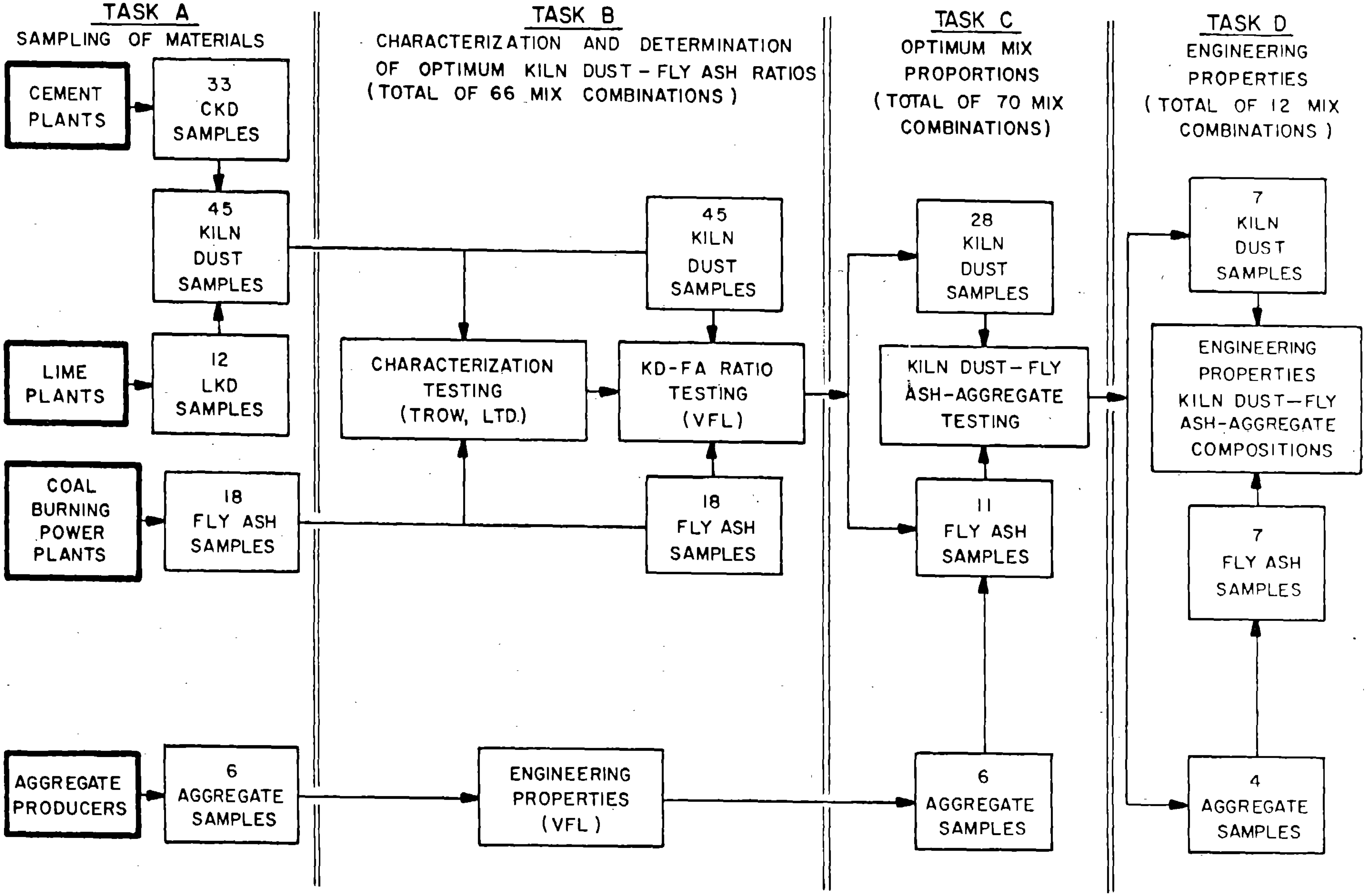
The engineering properties of each selected mix combination were evaluated in terms of previous strength data from Task B and Task C mixes for each kiln dust and fly ash sample in this phase of the test program.

The technical data forthcoming from this investigation is based on a comprehensive sampling and testing program involving a substantial number of kiln dust, fly ash, and aggregate samples. The logic of the testing sequence relies upon an ongoing selection of representative materials and combinations of materials so that the total number of testing variables can be systematically reduced as the program proceeds from one task to the next. In this way, factors such as material composition, reactivity, and geographical location can be continually accounted for while the laboratory evaluation proceeds with a manageable number of samples at each level of testing.

Figure 3 is a graphical portrayal of the testing sequence involved in this investigation. This figure depicts the total number of material samples involved in the initial sampling and how these samples are handled and reduced in stepwise fashion as each of the work tasks progresses. A more detailed description of the sampling and testing procedures employed in selecting and evaluating these materials is contained in the following chapters.

FIGURE 3

SEQUENCE OF LABORATORY TESTING AND MATERIALS HANDLING



4. SELECTION OF MATERIALS FOR TESTING PROGRAM

The initial work task concerns the selection of material samples for use in the kiln dust-fly ash testing program. A wide variety of kiln dust and fly ash materials were sampled for use in laboratory testing, together with a number of typical aggregate types. The objective of this phase of the study was to select and obtain samples of kiln dust and fly ash that were representative of the broad spectrum of such materials that would be potentially available for use in pozzolanic road base systems.

4.1 Kiln Dust Sampling

The following factors were considered in the selection of representative kiln dust samples:

- Geographical location
- Kiln type and operation
- Fuel type(s)
- Variations in raw feed materials
- Dust collection system
- Dust recycling procedures (if any)
- Disposal or storage practices
- Number and size of cement or lime companies

Prior to the selection of actual sampling sites, a review was made of available literature or data pertaining to locations, collection techniques, and characteristics of kiln dusts from the production of either portland cement or lime. The literature review was enhanced by publications from and discussions with representatives of such trade associations as the Portland Cement Association, the National Lime Association, and the American Pozzolanic Concrete Association. Based on the literature review and follow-up discussions with trade association representatives, candidate locations were selected for the sampling of kiln dusts.

4.1.1 Cement Kiln Dust Samples

Table 1 is an alphabetical listing of the company, plant location, kiln type and fuel used for each source of cement kiln dust obtained during the sampling program. Figure 4 is a map of the United States showing the locations of these cement kiln dust samples. A total of 33 cement dust samples were received, representing 20 different cement companies. Included among these 33 samples are three samples of stockpiled kiln dust. Of the 33 cement dust samples, 17 are from wet process plants and 16 are from dry process plants. The overwhelming majority of the samples (28) are from coal-fired cement plants, although two samples are from gas-fired plants and three other samples were obtained from plants using coal as a primary fuel, with either gas or oil as the auxiliary fuel.

4.1.2 Lime Kiln Dust Samples

Table 2 lists the company, plant location, kiln type, type of lime-

Table 1

SOURCES OF CEMENT KILN DUST SAMPLES

	Cement Company	Plant Location	Kiln Process	Fuel Type
1.	Atlantic Cement	Ravena, New York	Wet	Coal
2.	Columbia Cement	Zanesville, Ohio	Wet	Coal
3.	General Portland	Chattanooga, TN	Wet	Coal
4.	General Portland	Paulding, OH	Wet	Coal
5.	General Portland	Tampa, Florida	Wet	Coal
6.	Gifford-Hill Company	Clarkdale, Arizona	Dry	Coal
7.	Gifford-Hill Company	Oro Grande, Calif.	Dry	Coal
8.	Ideal Basic Industries	Ada, Oklahoma	Wet	Coal
9.	Ideal Basic Industries	Castle Hayne, NC	Wet	Coal
10.	Ideal Basic Industries	Florence, Colorado	Wet	Coal & Oil
11.	Kaiser Cement	Lucerne Valley, CA	Dry	Coal
12.	Keystone Cement	Bath, Pennsylvania	Wet	Coal
13.	Lehigh Cement	Mitchell, Indiana	Dry	Coal
14.	Lehigh Cement	Union Bridge, MD	Dry	Coal
15.	Lone Star Industries	Dixon, Illinois	Dry*	Coal
16.	Lone Star Industries	Houston, Texas	Wet	Gas
17.	Lone Star Industries	Roanoke, Virginia	Dry*	Coal
18.	Marquette Cement	Neville Island, PA	Wet	Coal
19.	Martin Marietta	Atlanta, Georgia	Dry	Coal
20.	Martin Marietta	Calera, Alabama	Dry	Coal
21.	Medusa Corporation	York, Pennsylvania	Wet	Coal
22.	Monarch Cement	Humboldt, Kansas	Dry*	Coal & Gas
23.	National Gypsum	Alpena, Michigan	Dry	Coal
24.	Northwestern States	Mason City, Iowa	Dry	Coal
25.	Oregon Portland	Lake Oswego, Oregon	Wet	Coal & Oil
26.	River Cement	Festus, Missouri	Dry	Coal
27.	Santee Cement	Holly Hill, S.C.	Wet	Coal
28.	South Dakota Cement	Rapid City, S.D.	Wet	Coal
29.	Texas Industries	Artesia, Mississippi	Wet	Gas
30.	Texas Industries	Midlothian, Texas	Wet	Coal

*One or more kilns equipped with a suspension preheater.

NOTE: Source listing is alphabetical and does not correspond with coding of test samples.

FIGURE 4

LOCATIONS OF CEMENT AND LIME KILN DUST SAMPLES

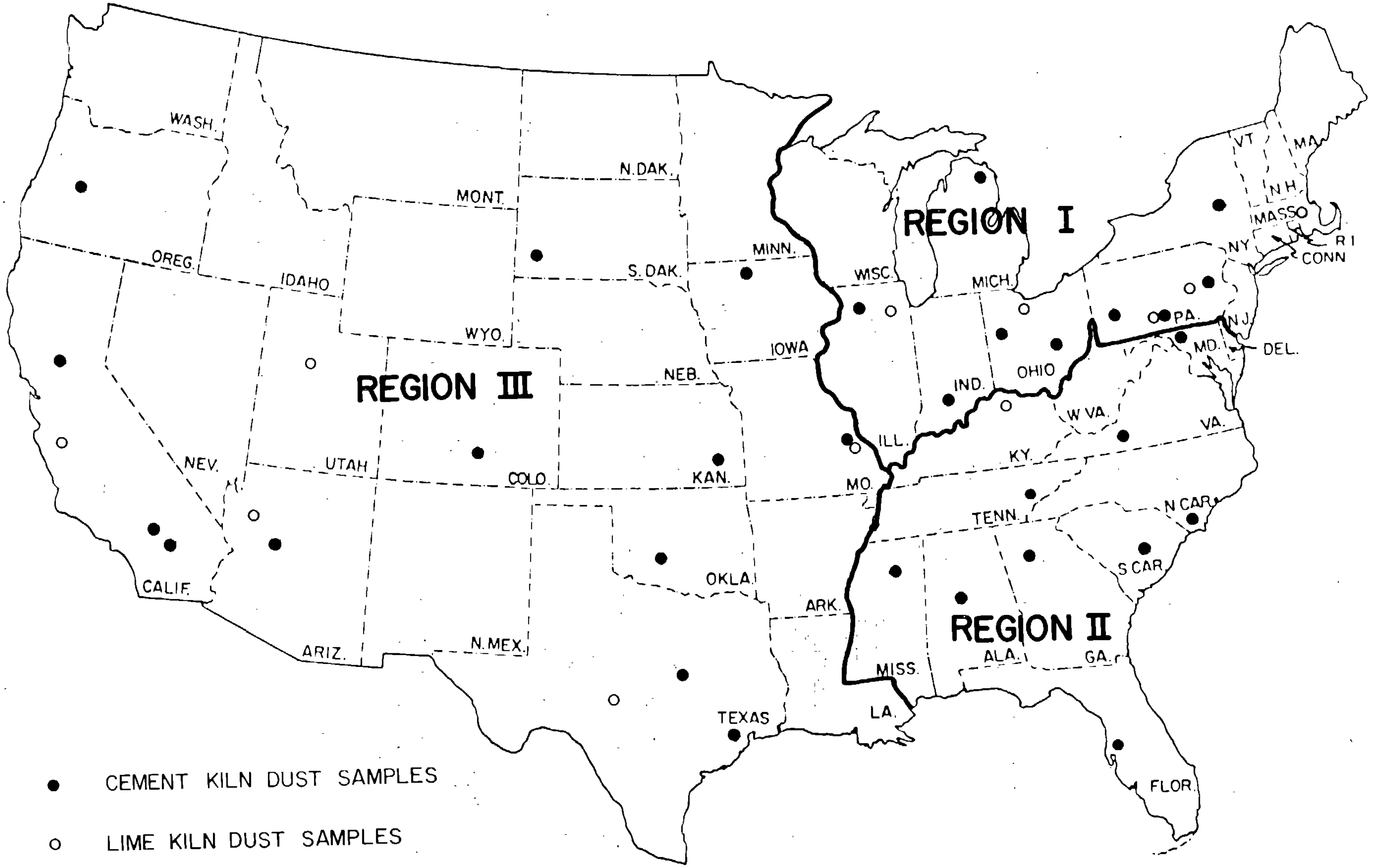


Table 2

SOURCES OF LIME KILN DUST SAMPLES

	Lime Company	Plant Location	Kiln Type	Type of Limestone	Fuel Type
1.	J.E. Baker Company	York, PA	Rotary*	Dolomitic	Coal
2.	Bethlehem Mines	Annville, PA	Rotary	High Calcium	Coal
3.	Chemical Lime	Clifton, TX	Rotary	High Calcium	Coal
4.	Dravo Lime	Maysville, KY	Rotary	High Calcium	Coal
5.	Flintkote Company	Grantsville, UT	Rotary	Dolomitic	Coal
6.	Flintkote Company	Nelson, Arizona	Rotary	High Calcium	Coal
7.	Kaiser Refractories	Natividad, CA	Rotary	Dolomitic	Oil & Gas
8.	Marblehead Lime	South Chicago, Illinois	Rotary	High Calcium	Coal
9.	Martin Marietta	Woodville, OH	Rotary	Dolomitic	Coal
10.	Mississippi Lime	Ste. Genevieve, MO	Rotary	High Calcium	Coal
11.	Pfizer, Inc.	Adams, MA	Fluosolids	High Calcium	Oil

*Produces a dead-burned dolomite product.

NOTE: Source listing is alphabetical and does not correspond with coding of test samples.

stone burned, and fuel used for each source of lime kiln dust obtained during the sampling program. The locations of these lime kiln dust samples are also shown in Figure 4. A total of 12 lime dust samples were received, representing 10 different lime companies. There is also one stockpiled kiln dust among the 12 lime dust samples. Eight lime dust samples are from kilns which produce high calcium lime, while four samples are from kilns which produce dolomitic lime. Nine of the dust samples were obtained from coal-fired plants, with the remaining three dust samples obtained from plants which burn oil as the primary kiln fuel.

4.1.3 Summary of Kiln Dust Sampling

Geographically, the United States was subdivided into three different regions:

Region I - Northeast and Great Lakes

Many states in this region are familiar with pozzolanic pavements, particularly Illinois, Ohio, and Pennsylvania. Most states in this region do experience severe winter weather with a relatively high number of freeze-thaw cycles.

Region II - Southeast

Very few states in this region are familiar with pozzolanic pavements. Most states in this region experience more moderate winter temperatures with comparatively less cyclic freezing and thawing.

Region III - Midwest and Far West

Most states in this part of the country (west of the Mississippi River) are not very familiar with pozzolanic pavement technology, with several notable exceptions (Arizona, Missouri, North Dakota, and Texas). This region has high potential for use of pozzolanic pavements because of the increasing availability of Class C (western) fly ashes. A wide variety of temperature conditions are found in this region, from bitterly cold winters in Minnesota to blistering summers in Arizona.

The geographical boundaries of these three regions, as shown in Figure 4, encompass principally the Mississippi River, the Ohio River, and the Mason-Dixon Line. There are a total of 14 states in Region I, 12 states in Region II, and 22 states in Region III.

During the selection of kiln dust samples, a conscious effort was made to achieve a fairly even geographical distribution of these samples, insofar as it was practical to do so. A study of Figure 4 reveals that the kiln dust samples for this program were obtained from 28 states throughout the entire country.

Of the 33 cement kiln dust samples collected in this program, 11 were obtained from Region I, 9 from Region II, and 13 from Region III. Of the

12 lime kiln dust samples collected in this program, 6 were obtained from Region I, 1 from Region II, and 5 from Region III. Out of a total of 45 kiln dust samples, 17 were obtained from Region I, 10 were from Region II, and 18 were from Region III.

The following table summarizes the random distribution of the dust sampling phase of this program.

Region	No. of States in Region	No. of States Sampled	No. of Cement Dust Samples	No. of Lime Dust Samples	Total No. of Dust Samples
I	14	7	11	6	17
II	12	10	9	1	10
III	22	11	13	5	18
TOTAL	48	28	33	12	45

4.1.4 Kiln Dust Sampling Procedure

The main concern during the sampling phase of this program was to obtain a representative sample of each material in sufficient quantity for testing. It was initially determined that 136.2 kilograms (300 pounds) of kiln dust would be required from each sampling location in order to provide a sufficient sample for evaluation throughout the entirety of the testing program. Although the number of dust samples to be tested were decreased in the later stages of the program, the dusts that were to be evaluated in Tasks C and D were not known during initial sampling. Therefore, with few exceptions, the maximum required amount (approximately 300 pounds) of kiln dust was obtained from each sampling source.

To assure that each dust sample was as representative as possible, a special sampling procedure was developed and used. All dust sampling was performed by operations personnel of the respective cement or lime companies. At each plant location, individual grab samples of 9.08 kilograms or 20 pounds each were obtained over a 15-day sampling period. Each sample was taken from the same location within a respective plant's dust collection and disposal system, usually at the discharge point where waste dust is unloaded for final disposal. It was reasoned that waste dust samples obtained at a plant's discharge point would generally be indicative of the type of dust that a particular plant would make available for a prospective user.

The sampling procedure stipulated that individual 20-pound grab samples be obtained once a day for 15 consecutive days and be taken at a random time each day. Each individual sample was placed into a double sealed plastic bag. No dust sample was taken during any kiln upset period (start-up or shutdown), and all grab samples were taken only during times of normal kiln operation. A copy of the sampling procedure is included in the Appendix.

All fifteen individual 20-pound grab samples were packed into a single container, normally a 208 liter (55-gallon) steel drum, and shipped to Valley Forge Laboratories. Small companion samples were taken at many of the plants and were chemically analyzed to provide an indication of the degree of dust variation at an individual cement or lime plant over the 15-day sampling period of normal kiln operation. Once the individual grab samples were received, they were blended into one composite sample, which was then used for subsequent laboratory testing.

There were, of course, several instances in which less than a 136.2 kilograms (300 pound) total sample of kiln dust was obtained, or where fewer than 15 individual grab samples were provided. These instances usually involved one or more of the following conditions:

- An unexpected and prolonged kiln shutdown period partway through the dust sampling program.
- Extensive recycling of kiln dust at a particular plant, resulting in comparatively small quantities of waste kiln dust.
- Reduction in sample size due to some plants being unable to conduct dust sampling over a 15-day period.
- Obtaining a sample of stockpiled kiln dust from selected plants having large dust stockpiles. The stockpiled dust sample usually involved 90.8 to 136.2 kilograms (200 to 300 pounds) of dust, but the number of individual grab samples was generally ten or less.

A total of four stockpiled dust samples were received. Three of the stockpiled dust samples were from cement plants, one was from a lime plant. Two of these stockpiled dust samples, one a cement dust and one a lime dust, were provided in 18.9 liter (five-gallon) containers. Two other cement kiln dust samples and one other lime dust sample were also shipped in five-gallon containers. Of the 45 dust samples, therefore, a total of five represented single grab samples. The remaining 40 material sources were composite samples that were taken over a 15-day period in accordance with the sampling procedure developed for this program.

All kiln dust samples are identified by code number throughout the entire testing program in order to assure confidentiality with respect to the origin and properties of each dust source. All cement kiln dusts are identified by the prefix "CD", followed by the sample number. All lime kiln dusts are identified by the prefix "LD", followed by the sample number. All dust samples were assigned code numbers based on the chronological order in which they were received. All laboratory test data pertaining to individual kiln dust samples is identified and presented in this report only according to code number.

4.2 Fly Ash Sampling

The following factors were considered in the selection of representative fly ash samples:

- Geographical location
- Type and sources of coal burned
- Utility company
- Power plant operating characteristics
- Ash marketing organization
- Prior use of ash in pozzolanic pavement.

Prior to the selection of fly ash sampling locations, a review was made of available literature or data pertaining to coal-fired power plant locations, operating characteristics, fuel consumption patterns, and fuel sources. Special advice and assistance was also provided by the National Ash Association and knowledgeable utility waste marketing consultants regarding prospective sampling locations. Based on a review and evaluation of the information provided from these various sources, candidate locations were selected for the sampling of fly ashes.

4.2.1 Summary of Fly Ash Sampling

A total of 18 fly ash samples were collected for evaluation in the testing program. Although the main purpose of this investigation is to evaluate kiln dusts as pozzolanic road base materials, it is also important to match the kiln dust samples with a sufficient number and variety of fly ashes to effectively cover the spectrum of available ashes which could conceivably be used in such combinations. Therefore, efforts were made to obtain fly ash samples from the burning of bituminous, subbituminous, and lignite coals. At least one fly ash sample was obtained from each of the top five ash producing states. Of the ten states burning the most utility coal, fly ash samples were obtained from power plants in eight of these states. A conscious attempt was also made to achieve an overall geographical distribution of the fly ash samples obtained for this program.

Table 3 lists the utility company, power plant name and location, and the type of coal burned at each of the 18 locations where fly ash samples were obtained for use in this testing program. Figure 5 is a map of the United States showing the locations where these fly ash samples were collected. Of the 18 fly ash samples, 11 are Class F fly ashes from the burning of bituminous coal; 1 is a Class F western bituminous coal fly ash; 4 are Class C fly ashes from the burning of sub-bituminous coal (including one by-product from a dry scrubbing system), 1 is a Class C fly ash from the burning of lignite coal, and 1 is a fly ash from the burning of a blend of bituminous and sub-bituminous coal (probably a Class C fly ash).

In most cases, fly ash sampling was arranged through the efforts of the National Ash Association with reputable ash marketing organizations. This was done to assure that ash samples of consistent quality with generally predictable characteristics were incorporated into the testing program.

4.2.2 Fly Ash Sampling Procedure

For the fly ash sampling, it was considered important to obtain a sufficient quantity of fly ash representative of the ash material normally being generated at a particular power plant. Preliminary computations indicated that 363.2 kilograms (800 pounds) of fly ash would be required for testing throughout the entirety of the program. This was estimated as the amount of

Table 3

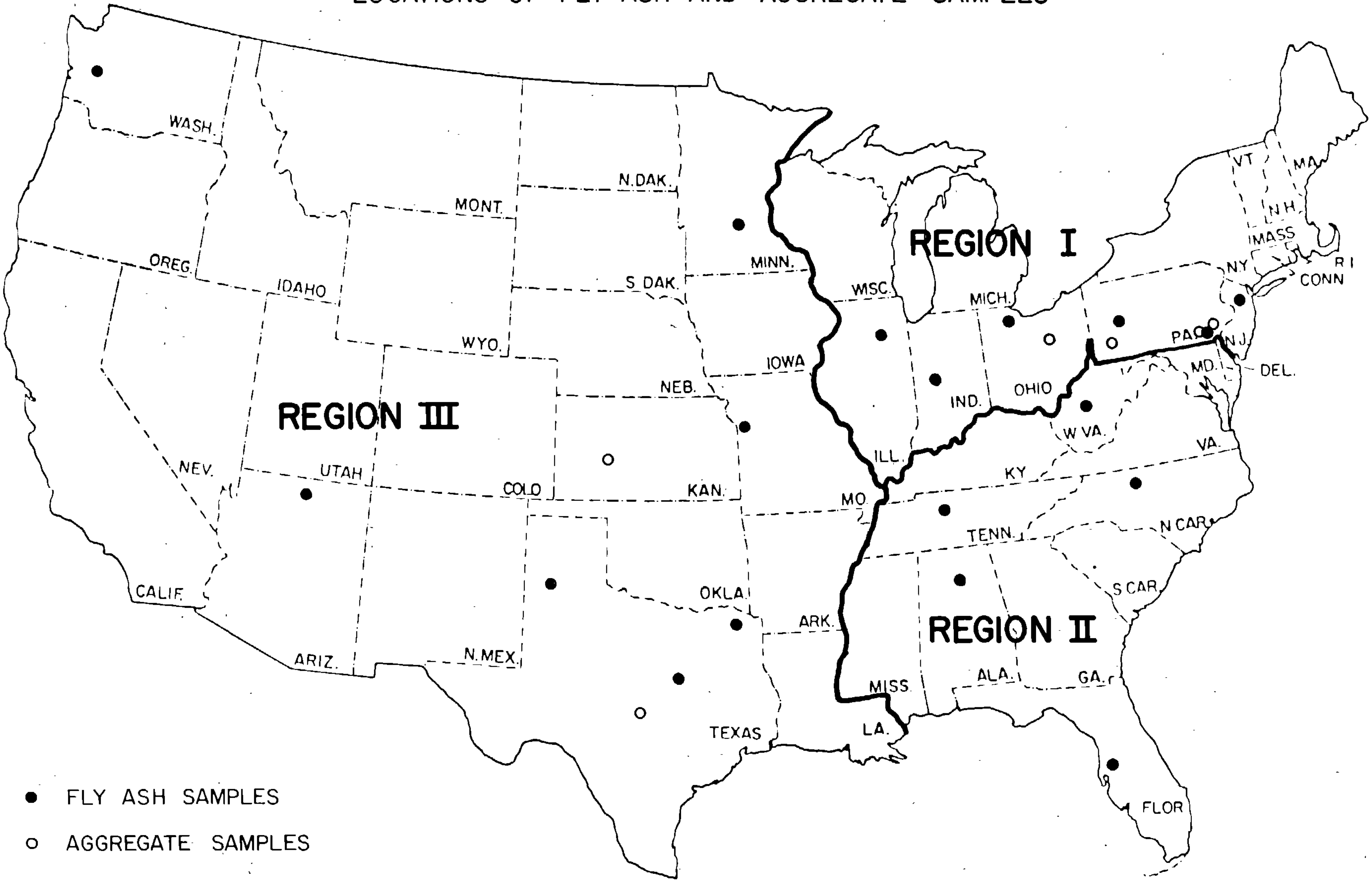
SOURCES OF FLY ASH SAMPLES

	Utility Company	Power Plant	Plant Location	Coal Burned
1.	AEP Service Corp.	John Amos	St. Albans, WV	Bituminous
2.	Alabama Power	Gaston	Wilsonville, AL	Bituminous
3.	Commonwealth Edison	Joliet	Joliet, IL	Sub-bituminous
4.	Duke Power	Belews Creek	Walnut Cove, NC	Bituminous
5.	Indianapolis P & L	Stout	Indianapolis, IN	Bituminous
6.	Kansas City P & L	Hawthorn	Kansas City, MO	Bituminous & Sub-bituminous
7.	Northern States Power	Riverside	Minneapolis, MN	Sub-bituminous
8.	Pacific Power & Light	Centralia	Centralia, WA	Bituminous
9.	Pennsylvania Electric	Keystone	Shelocta, PA	Bituminous
10.	Philadelphia Electric	Eddystone	Chester, PA	Bituminous
11.	Public Service Electric & Gas	Hudson	Jersey City, NJ	Bituminous
12.	Salt River Project	Navajo	Page, AZ	Bituminous
13.	Southwest Electric Power	Welsh	Cason, TX	Sub-bituminous
14.	Southwest Public Service	Harrington	Amarillo, TX	Sub-bituminous
15.	Tampa Electric	Big Bend	Tampa, FL	Bituminous
16.	Tennessee Valley Authority	Gallatin	Gallatin, TX	Bituminous
17.	Texas Power & Light	Big Brown	Fairfield, TX	Lignite
18.	Toledo Edison	Bayshore	Toledo, OH	Bituminous

NOTE: Source listing is alphabetical and does not correspond with coding of test samples.

FIGURE 5

LOCATIONS OF FLY ASH AND AGGREGATE SAMPLES



fly ash needed to fill two 208 liter (55-gallon) steel drums. Since it was not possible to know at the time of sampling just which fly ashes would be tested in all phases of the program, the minimum required amount (approximately 363.2 kilograms or 800 pounds) of fly ash was obtained from each sampling source.

Representatives of ash marketing organizations or utility companies were requested to collect one drum of their fly ash on each of two consecutive days, provided the boiler operation was normal during sampling. The time of sampling was randomly chosen on each day. All suppliers of fly ash were also requested to provide an analysis of each daily grab sample and background information on previous analyses of fly ash samples taken from the same plant, in order to establish that the samples provided were representative samples falling within the normal compositional range for that plant.

All fly ash samples were also provided with a code number to allow for ease of identification and maintain a degree of confidentiality. All fly ash samples were identified by the prefix "FA", followed by the sample number. All fly ash samples were assigned code numbers based on the chronological order in which they were received. All laboratory test data pertaining to individual fly ash samples is identified and presented in this report only according to code number.

4.3 Aggregate Sampling

A total of six aggregate samples were obtained for use in the later phases of this study. The intent of the aggregate sampling was to obtain materials representing a variety of commercial aggregate types that have been and will be used in pozzolanic road base compositions, including crushed stone, sand and gravel, and slag. In addition, since many kiln dusts are known to be relatively high in alkali, an attempt was also made to acquire a sample of aggregate known to be reactive in the presence of alkali, in order to evaluate the behavior of kiln dust-fly ash-aggregate mixtures with potential alkali-aggregate reactivity.

In order to assist in notifying potentially cooperative aggregate producers and arranging for possible aggregate sampling at relatively typical production locations, initial contacts were made with representatives of trade associations representing various facets of the aggregate production industry. The organizations contacted were the National Crushed Stone Association, the National Sand and Gravel Association, and the National Slag Association. Each organization identified several recommended plant locations for the possible sampling of each different type of aggregate desired for the test program, together with the name and telephone number of the appropriate contact person at each location. In most cases, a representative of the trade association also established initial contact to briefly explain the test program and the purpose of the sample.

The name of each of the six aggregate producers, their plant location, and a description of the type of aggregate sample provided by each is presented in Table 4. Figure 5 is a map of the United States showing also the locations where these aggregate samples were obtained. Approximately 1.1 tonnes (one ton) of graded aggregate was provided by each producer, with the

TABLE 4

SOURCES OF AGGREGATE SAMPLES

Aggregate Producer	Source of Aggregate	Type of Aggregate	Aggregate Code Letter
Central Allied Enterprises	North Canton, Ohio	Siliceous sand and gravel	D
Dusquesne Slag Company	Pittsburgh, Pennsylvania	Air-cooled blast furnace slag	C
General Crushed Stone Company	Glen Mills, Pennsylvania	Granitic gneiss	B
Gifford-Hill and Company	New Braunfels, Texas	Calcitic limestone	E
McCoy Quarry, Inc.	Bridgeport, Pennsylvania	Dolomitic limestone	A
Siebert Sand Company	Ness City, Kansas	River sand and gravel	F

aggregate generally having a top size of 38.1 mm (1-1/2 in.) with 10 percent or less passing a No. 200 sieve. The aggregate samples consisted of a high calcium limestone, a dolomitic limestone, a granitic gneiss, a siliceous sand and gravel, a river gravel, and an air-cooled blast furnace slag. One of these samples is also considered an alkali-reactive aggregate.

Each aggregate was assigned a code letter (A through F) based on the chronological order in which it was received. This coding is referenced in Table 4. The geographical distribution of the fly ash and aggregate samples is shown in Figure 5 with a breakdown into the three geographical regions described earlier.

5. CHARACTERIZATION OF KILN DUST AND FLY ASH SAMPLES

5.1 Scope and Purpose of Characterization Testing

The characterization testing of the kiln dust and fly ash involved four main aspects:

1. Physical properties (particle size distribution, specific gravity, Blaine fineness and pH);
2. Chemical properties (major oxides, loss on ignition, carbon and carbon dioxide);
3. Mineralogical composition (major minerals and free lime); and
4. Pozzolanic/hydraulic indices (mortar cube strengths for accelerated and ambient curing conditions).

From the physical, chemical, mineralogical and index data developed, it was anticipated that key parameters such as free lime, fineness, alkalies, etc. might be identified and related to those kiln dust - fly ash-aggregate compositions demonstrating satisfactory laboratory strength and engineering properties. These key parameters could then be used in practice to select suitable kiln dusts and predict their performance in pozzolanic base construction.

Where possible, standard ASTM and cement/lime industry testing procedures were adopted. Special care was taken to ensure the quality of the characterization data by using representative specimens; avoiding any chance of contamination; minimizing carbonization and moisture influences; replicating/comparing with known standards; and completing tests on the standard cement and limes used. (26)

While the full characterization data developed are given in Tables 6 to 14, with detailed notes, a brief description of test procedures and general trends is given below. An analysis of the characterization findings is given in other task sections where kiln dust-fly ash-aggregate composition data are developed.

5.2 Physical Characterization Test Methods and Results

The physical characterization test results for cement kiln dusts, lime kiln dusts and fly ashes are given in Tables 5, 6, and 7, respectively. The test procedures used were: particle size distribution (ASTM D422, sedimentation in water shown to be suitable); specific gravity (air comparison pycnometer); Blaine fineness (ASTM C204); and slurry pH (15 gm of specimen in 150 ml distilled, deionized water (pH 7.8), stirred 1 minute, pH of slurry).

An important physical characteristic of both kiln dusts and fly ashes is their particle size distribution, particularly the relative amount of fine grained particles (smaller than 200 mesh size). Fineness or surface area is also considered to be another key physical characteristic because pozzolanic/hydraulic reactions are surface dependent. The fineness characteristic is best analyzed by Blaine fineness or percent residue on 325 mesh

TABLE 5

PHYSICAL CHARACTERIZATION TEST RESULTS FOR CEMENT KILN DUSTS

	PARTICLE SIZE DISTRIBUTION PERCENT PASSING							OTHER		
SAMPLE NUMBER	TOP SIZE	60 MESH	200 MESH	325 MESH	0.02 mm	0.01 mm	0.006 mm	SG	BLAINE FINENESS	pH[c]
CD-1		100	99	97.5	87.5	3		2.76	9090	11.9
CD-2	#50	99.6	96.7	93	11	0.5		2.78	4890	11.9
CD-3	#20	97.5	83.2	71	2.5	0		2.78	5870	11.9
CD-4	#50	98.7	84	70	28			2.76	7190	11.9
CD-5	#14	97.2	71	50	14			2.87	7550	12.1
CD-6	#50	99.9	84	61	19			2.74	9980	12.1
CD-7	#50	98.7	86	76.5	35	0.3		2.84	5120	11.9
CD-8	#50	98.6	72	52	21.5			2.84	4610	11.9
CD-9	#10	96.5	85.7	77	1.2	0.3	0	2.85	4940	12.0
CD-10			100	97.5	76			2.79	10760	12.0
CD-11	#50	99.5	95.2	91.5	55	4.4	2.2	2.76	8130	11.8
CD-12	#50	99.9	94	89.5	77.5	44	19	2.74	10370	11.9
CD-13	#10	97.8	79.5	59.5	21.5			2.84	7110	11.9
CD-14	#50	98.6	80	68	38			2.78	6810	12.0
CD-15	#50	99	89	82	67	27	19.3	2.69	7090	11.5
CD-16	#50	99.5	94	88	63			2.77	8700	12.0
CD-17	#50	98.5	79.3	63	34.5			2.79	10010	12.1
CD-18	#50	99.5	97.4	96.3	80	3	1.3	2.74	9120	12.0
CD-19	#50	99.5	88.5	81.2				2.85	5680	12.1
CD-20	#50	99.5	90	80	3.5			2.75	6090	12.1
CD-21	#50	97	78	66	4.5	0		2.79	4460	12.1
CD-22[a]	1/2" (99.5%)	32	12							
CD-22[b]	#10	79	57.5	46.5	28	14	8.5	2.60	3740	11.8
CD-23[a]	1/2" (95%)	11	2							
CD-23[b]	#10	76	57	41	29.5	22	16.8	2.78	13900	11.2
CD-24	#50	99.5	85.5	68				2.93	5630	12.0
CD-25			100	97.5	86.5	0		2.70	13060	12.0
CD-26	3/4"	29.5	17.5	12.5	9	2.5	1.3	2.48	6950	12.0
CD-27	#50	99.5	86	72	25	0		2.79	5520	12.0
CD-28	#50	99.6	98	95.6	4.7	3		2.86	7370	12.1
CD-29	#50	99	86	79				2.83	5600	12.0
CD-30	#100		98.8	97.7	80	2.5	1.8	2.76	8780	11.9
Calcitic Hydrated Lime			100	98	91	0		2.31		

Notes:
a. As received.
b. Ground.
c. 15 gm in 150 ml distilled, deionized water, stirred 1 minute, pH of slurry, (pH of water 7.8).

TABLE 6

PHYSICAL CHARACTERIZATION TEST RESULTS FOR LIME KILN DUSTS

	PARTICLE SIZE DISTRIBUTION PERCENT PASSING							OTHER		
SAMPLE NUMBER	TOP SIZE	60 MESH	200 MESH	325 MESH	0.02 mm	0.06 mm	0.001 mm	SG	BLAINE FINENESS	pH[b]
LD-1	#20	99.5	89.3	73	0			2.96	2920	12.0
LD-2	#50	99.7	86.5	40				2.85	5180	12.0
LD-3	#10	90.5	78.3	65				2.87	3650	11.9
LD-4			100	98	49			2.73	10350	12.0
LD-5	#10	92.3	49.5	4				2.89	1310	12.0
LD-6	#10	98.9	88.5	69				2.83	2180	12.0
LD-7	#10	97	79	56				2.93	1870	12.0
LD-8[a]										
LD-9[a]										
LD-10	#50	98.5	62.5	43	23.3	13	7.6	2.98	2090	12.0
LD-11	#10	84.8	74	56				3.04	1750	12.0
LD-12	#10 (99.5%)	80.5	57	43	19.5	4.5		2.83	2630	11.9

NOTES:
[a] Testing to be completed.
[b] 15 gm in 150 ml distilled, deionized water, stirred 1 minute, pH of slurry, (pH of water 7.8).

TABLE 7

PHYSICAL CHARACTERIZATION TEST RESULTS FOR FLY ASHES

		PARTICLE SIZE DISTRIBUTION PERCENT PASSING						OTHER		
SAMPLE NUMBER	TOP SIZE	60 MESH	200 MESH	325 MESH	0.02 mm	0.06 mm	0.001 mm	SG	BLAINE FINENESS	pH[a]
FA-1	#10	99	94	85	50	17.7	10.3	2.65	4170	11.2
FA-2	#10	98.2	92.8	84	43.9	11.2	7	2.74	3550	11.6
FA-3		100	95	85	66.8	26.3	11	2.41	3360	10.4
FA-4	#10	99.4	92.8	83	54	27	18	2.31	3790	11.4
FA-5	#10	99.5	91	81.5	61.2	34	18.1	2.18	2620	10.0
FA-6	NOT TESTED							2.62		
FA-7	#10	98.9	87.2	78	54	30	17	2.28	2820	8.7
FA-8	#10	99	89	80	54.5	29.7	17	2.45	2820	9.8
FA-9		100	96.3	89	62	37	22.3	2.44	3150	11.0
FA-10	#10	98.8	92	84	7	2	1	2.70	3900	11.4
FA-11	#10	99.2	90	78.5	53.7	31	17.5	2.52	2880	11.3
FA-12		100	96.7	94	70			2.48	10060	11.6
FA-13	#10	98	88.7	76	47.8	25	14	2.45	2360	4.2
FA-14	#10	97.2	84	72	47	25.8	14	2.30	2870	5.5
FA-15	#10	99	93.5	83	62.5	42.7	26.8	2.38	3510	5.0
FA-16	#50	99.8	99	96	82.5	60	35	2.49	5080	3.5
FA-17	#50	99.9	88	76	50.3	28.8	16.3	2.27	3160	8.2
FA-18	#50	99.9	93.7	83	42	22	11.8	2.24	3360	4.3
FA-19	#50	99.9	93	84	48	22	13.2	2.38	3640	10.0

NOTES: a. 15 gm in 150 ml distilled, deionized water, stirred 1 minute, pH of slurry, (pH of water 7.8).

sieve. Attempts to optically (100 to 200 magnification) determine cement content in a petrographic microscope were not fruitful, given the many constituents and sizes involved.

5.3 Chemical Characterization Test Methods and Results

The chemical characterization test results for cement kiln dusts, lime kiln dusts and fly ashes are given in Tables 8, 9, and 10, respectively. The test procedures used for specimens crushed to passing 200 mesh were: major oxides (X-ray fluorescence); SO_3 (Leco, ASTM C25); LOI (105°C. - oven, 550°C, 1050°C. - muffle furnace); and carbon, total carbon and CO_2 (Standard Methods). Loss on ignition (LOI) at 1050°C. (or CO_2), along with CaO and alkalies are considered to be key chemical characteristics. Higher LOI values indicate carbonation or loss of effectiveness.

5.4 Mineralogical Composition Test Methods and Results

The mineralogical composition results for cement kiln dusts, lime kiln dusts and fly ashes are also given in Tables 8, 9, and 10, respectively. X-ray diffraction was used to quantify the major minerals, including free lime, for specimens crushed to passing 200 mesh. This was accomplished by measuring specific peak intensities of each crystalline mineral encountered relative to that of the 10 percent by weight CaF added internal standard. Free lime calibration was achieved against glycol methanol extraction controls as indicated in Tables 12 and 13. Free lime and, to a lesser extent, the sulphate content, are considered to be key mineralogical characteristics. Lime is normally used as the primary reactive component in pozzolanic base construction. Sulfate is a key constituent in the formation of ettringite.

5.5 Compressive Strength Development and Comparisons, Test Methods and Results (Pozzolanic/Hydraulic Indices)

The compressive strength development and comparisons (pozzolanic/hydraulic indices) for cement kiln dusts, lime kiln dusts and fly ashes are given in Tables 11, 12, and 13, respectively. All of this testing was in accordance with ASTM C593, noting particularly ASTM C593 - Section 7.5 Proportioning, Consistency and Mixing of Mortars, and the notes in Tables 11, 12 and 13. For the cement kiln dusts and lime kiln dusts compressive strength development, fly ash FA-16 was selected as the control pozzolan, with calcitic hydrated lime as the control lime for fly ash compressive strength development. The pozzolanic index control (POZ CONT) was calcitic hydrated lime - FA-16 - silica sand, with the hydraulic index control (HYD CONT) Type 1 portland cement - FA-16 - silica sand. Accelerated 7-day strengths are considered the best indicator of pozzolanic reactivity, with ambient 28-day strengths the best indicator of hydraulic reactivity. While discussed in detail in later sections, the free lime, by simple inspection, show the highest "correlation" to strength development.

Table 8

CHEMICAL CHARACTERIZATION TEST RESULTS FOR CEMENT KILN DUSTS

PERCENT

SAMPLE NUMBER	CaO	Free Lime CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	LOI 1050°C.
CD-1	38.3	3.3	13.2	4.61	2.49	0.15	3.96	2.32	6.74	25.3
CD-2	44.5	4.1	17.1	4.84	1.15	0.27	2.91	1.97	3.82	22.8
CD-3	39.1	3.72	15.4	2.93	2.63	0.55	3.52	2.13	8.56	22.8
CD-4	37.2	0.3	12.5	4.18	2.02	0.68	4.70	1.51	6.79	27.3
CD-5	38.0	2.3	15.3	4.25	0.91	0.32	7.30	1.83	7.94	19.6
CD-6	25.8	0.2	9.71	2.21	1.13	1.35	15.3	1.77	17.40	19.5
CD-7	41.9	1.7	16.2	4.11	1.64	0.34	3.22	2.39	4.79	22.9
CD-8	39.4	1.1	17.7	4.07	0.92	1.20	3.90	2.84	3.47	22.7
CD-9	41.6	4.2	20.0	5.76	2.22	0.41	3.76	2.46	6.69	12.7
CD-10	45.9	4.8	11.9	2.92	1.39	0.07	1.54	2.04	6.24	28.2
CD-11	40.8	2.2	13.3	4.85	1.02	0.27	2.90	2.26	6.24	25.6
CD-12	44.4	0.4	12.0	3.13	1.66	0.08	2.86	1.27	3.30	31.8
CD-13	45.2	6.7	16.8	3.88	1.37	0.18	1.78	2.11	3.72	23.2
CD-14	34.6	0.3	15.1	4.24	1.83	0.58	7.05	2.06	8.64	22.9
CD-15	19.4	0.20	22.4	10.0	0.64	1.34	14.1	4.06	10.14	13.2
CD-16	37.4	1.2	15.2	4.75	1.96	0.48	5.03	2.78	6.37	24.0
CD-17	26.8	1.2	13.0	4.50	0.54	1.47	12.4	2.04	16.93	13.5
CD-18	47.6	4.2	9.91	3.08	1.33	0.11	1.08	1.21	2.92	31.6
CD-19	41.1	13.15	15.2	3.92	1.30	0.20	3.39	2.19	13.76	11.7
CD-20	45.5	4.8	14.0	3.39	1.16	0.28	2.50	1.26	2.40	28.4
CD-21	42.9	4.3	14.9	4.62	0.89	0.14	3.16	2.31	5.54	22.2
CD-22	39.6	0.0	17.6	4.42	2.04	0.20	2.60	2.04	3.75	26.6
CD-23*	31.4	0.0	11.7	3.18	0.97	0.13	1.65	2.16	8.24	40.4
CD-24	57.1	16.0	9.70	4.18	1.81	0.00	0.22	0.24	2.67	21.1
CD-25	37.9	0.0	8.85	2.98	1.15	0.36	7.94	1.51	11.74	27.5
CD-26*	44.2	0.0	11.9	3.24	1.73	0.27	2.92	1.45	2.40	30.2
CD-27	42.5	7.8	14.3	3.34	2.09	0.44	5.21	1.82	3.10	23.8
CD-28	49.7	21.3	13.2	3.24	1.73	0.40	4.03	1.48	3.02	18.7
CD-29	47.5	9.1	14.3	3.03	1.20	0.30	2.02	1.93	3.20	24.1
CD-30	43.0		16.0	3.97	3.28	0.28	2.09	2.20	2.15	27.1

*Stockpiled kiln dust sample.

Table 9

CHEMICAL CHARACTERIZATION TEST RESULTS FOR LIME KILN DUSTS

PERCENT

SAMPLE NUMBER	CaO	Free Lime CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	LOI 1050°C.
LD-1	28.5	3.4	9.19	5.27	20.5	0.21	0.49	6.82	6.37	18.2
LD-2	31.2	2.6* 5.1	2.46	0.74	23.5	0.00	0.09	0.94	2.80	37.4
LD-3	54.5	26.68* 26.4	9.94	4.16	0.49	0.03	0.22	1.98	7.97	14.2
LD-4	44.3	2.1	10.1	4.92	3.56	0.14	0.38	1.36	4.84	27.5
LD-5	66.1	40.8	1.92	0.48	2.16	0.00	0.13	0.43	1.72	19.6
LD-6	56.7	13.1	3.45	1.83	1.11	0.00	0.21	0.80	0.27	34.4
LD-7	58.0	14.5	3.21	1.18	0.43	0.00	0.10	3.48	2.20	27.6
LD-8**	31.2	0.0	1.74	0.71	23.3	0.05	0.03	1.30	3.50	39.7
LD-9	53.9	8.8	5.90	2.57	2.23	0.09	0.33	1.79	3.50	27.9
LD-10	35.6	2.9	0.62	0.06	23.8	0.00	0.00	0.56	0.87	36.2
LD-11	62.4	29.40* 29.7	12.7	4.85	0.70	0.09	0.19	1.36	2.05	8.47
LD-12	35.1	2.0	6.41	1.41	21.5	0.02	0.12	0.75	0.05	35.3

*Comparison by wet chemistry - glycol methanol extraction.
**Stockpiled kiln dust sample.

Table 10

CHEMICAL CHARACTERIZATION FOR FLY ASHES AND MISCELLANEOUS TEST MATERIALS

A. FLY ASHES

SAMPLE NUMBER	CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	LOI 1050°C
FA-1*	28.21 to 36.4	35.94 to 50.03	13.9 to 20.3	5.0 to 6.1			5.1 to 9.4	1.5 to 3.2	0.36
FA-2	14.6	38.4	13.0	1.36	0.40	2.04	20.6	3.30	1.62
FA-3*		47.3	25.7	1.2			14.1	0.66	2.90
FA-4	6.69	55.1	12.1	1.61	1.73	1.24	5.16	0.52	0.62
FA-5*	0.57 to 0.86	55.44 to 59.37	28.00 to 32.31	0.45 to 1.0	0.26 to 0.30	2.46 to 2.90	3.21 to 4.96	0.10 to 0.47	0.66
FA-6*	4.51	43.16	20.75			1.12	19.82	1.26	
FA-7	2.41	50.9	25.3	0.95	0.28	2.83	8.42	0.27	2.08
FA-8*	2.2 to 2.46	48.3 to 50.24	19.4 to 26.28	0.73 to 1.16	2.12 to 2.33		11.8 to 14.74	0.56 to 0.68	2.33
FA-9*	13.40	45.03	20.68	3.86	3.67		6.68	1.80	0.35
FA-10	26.3	34.8	17.3	4.73	1.72	0.42	5.31	3.15	0.23
FA-11	15.8	50.5	17.2	3.06	0.49	0.82	5.91	0.95	0.39
FA-12	20.6	30.3	13.0	3.16	0.36	0.39	4.76	16.36***	16.0
FA-13	1.53	44.1	19.6	0.70	0.33	2.39	21.5	0.77	4.93
FA-14	1.81	46.2	31.3	0.67	0.25	1.99	8.53	0.45	4.47

TABLE 10 - Continued

CHEMICAL CHARACTERIZATION FOR FLY ASHES AND MISCELLANEOUS TEST MATERIALS

A. FLY ASHES

SAMPLE NUMBER	CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	LOI 1050°C
FA-15	1.44	50.9	28.9	0.92	0.32	2.52	5.43	0.42	2.93
FA-16**	1.93	44.0	26.8	0.74	0.28	2.14	14.6	0.90	4.39
	1.70	48.9	28.2	0.91	0.36	2.55	7.43	0.45	4.47
FA-17	7.48	48.9	22.8	1.54	2.86	0.67	6.09	0.30	0.54
FA-18	1.67	48.9	28.3	0.92	0.38	2.51	7.48	0.40	4.23
FA-19	3.26	42.8	22.4	0.95	0.61	2.09	14.8	1.15	8.70
B. MISCELLANEOUS TEST MATERIALS									
Calcitic Hyd. Lime	65.2	0.98	0.42	1.31	0.00	0.28	0.22		26.9
Dolomitic Hyd. Lime	38.0	1.73	0.27	28.0	0.00	0.01	0.54		30.9
Type 1 PC	57.9	19.8	5.81	2.64	0.22	0.82	2.47		1.23

NOTES: *Data provided by fly ash supplier, except for LOI values.
**Two separate XRF samples prepared for FA-16.
***May be in partly sulphide form.

Table 11

CEMENT KILN DUST - FLY ASH (FA-16) - SILICA SAND MORTAR CUBES[a]

COMPRESSIVE STRENGTH DEVELOPMENT AND COMPARISONS

CD (180 g) - FA-16 (360 g) - SAND (1480 g) - WATER (TO MEET FLOW)

CEMENT KILN DUST	WATER USED mℓ	FLOW[b]	7 DAY[c] ACC STRENGTH psi	28 DAY[d] ACC STRENGTH psi	28 DAY[e] AMB STRENGTH psi	7 DAY ACC POZ[f] CONT	28 DAY ACC POZ[f] CONT	28 DAY AMB POZ[f] CONT	7 DAY ACC HYD[g] CONT	28 DAY ACC HYD[g] CONT	28 DAY AMB HYD[g] CONT
CD-1	300	74.50	175	190	100	0.15	0.15	1.00	0.07	0.06	0.06
CD-2	297	70.25	361	363	310	0.30	0.29	3.10	0.14	0.12	0.17
CD-3	292	65.25	481	525	251	0.40	0.41	2.51	0.19	0.17	0.14
CD-4	302	71.75	96	101	77	0.08	0.08	0.77	0.04	0.03	0.04
CD-5	310	66.25	113	156	184	0.09	0.12	1.84	0.04	0.05	0.10
CD-6	310	65.50	96	106	125	0.08	0.08	1.25	0.04	0.03	0.07
CD-7	310	65.00	108	171	260	0.09	0.13	2.60	0.04	0.06	0.14
CD-8	310	68.25	220	231	361	0.18	0.18	3.61	0.09	0.07	0.20
CD-9	300	69.50	645	710	733	0.54	0.56	7.33	0.25	0.23	0.41
CD-10	300	72.00	195	172	140	0.16	0.14	1.40	0.08	0.06	0.08
CD-11	300	74.25	137	163	135	0.11	0.13	1.35	0.05	0.05	0.08
CD-12	300	74.25	57	53	49	0.05	0.04	0.05	0.02	0.02	0.03
CD-13	315	67.50	510	515	411	0.42	0.40	4.11	0.02	0.17	0.23
CD-14	305	72.50	78	90	68	0.06	0.07	0.68	0.03	0.03	0.04
CD-15	300	71.50	21	26	20	0.02	0.02	0.02	0.01	0.01	0.01
CD-16	300	68.75	117	113	78	0.10	0.10	0.78	0.05	0.04	0.04
CD-17	310	68.25	175	204	164	0.15	0.16	1.64	0.07	0.07	0.09
CD-18	300	74.00	170	207	156	0.14	0.16	1.56	0.07	0.07	0.09
CD-19	300	67.50	1475	1763	999	1.23	1.38	9.99	0.58	0.57	0.56
CD-20	300	70.25	264	300	207	0.22	0.24	2.07	0.10	0.10	0.12
CD-21	300	73.25	557	561	467	0.46	0.44	4.67	0.22	0.18	0.26
CD-22[h]	300	66.00	35	26	32	0.03	0.02	0.32	0.01	0.01	0.02
CD-23[h]	350	66.50	14	6 (Plastic)	No Set	0.01	0.00	0.00	0.00	0.00	0.00
	350	68.00	No Set	No Set	No Set	0.00	0.00	0.00	0.00	0.00	0.00
CD-24	310	72.50	1169	1194	467	0.97	0.94	4.67	0.46	0.39	0.26
CD-25	320	72.00	32	34	14	0.03	0.03	0.14	0.01	0.01	0.01
CD-26[h]	335	71.25	214	244	142	0.18	0.19	1.42	0.08	0.08	0.08

Table 11 - Cont.

CEMENT KILN DUST - FLY ASH (FA-16) - SILICA SAND MORTAR CUBES[a]

COMPRESSIVE STRENGTH DEVELOPMENT AND COMPARISONS

CD (180 g) - FA-16 (360 g) - SAND (1480 g) - WATER (TO MEET FLOW)

CEMENT KILN DUST	WATER USED	FLOW[b]	7 DAY[c] ACC STRENGTH psi	28 DAY[d] ACC STRENGTH psi	28 DAY[e] AMB STRENGTH psi	7 DAY ACC POZ[f] CONT	28 DAY ACC POZ[f] CONT	28 DAY AMB POZ[f] CONT	7 DAY ACC HYD[g] CONT	28 DAY ACC HYD[g] CONT	28 DAY AMB HYD[g] CONT
CD-27	300	69.75	318	350	355	0.26	0.27	3.55	0.12	0.11	0.20
CD-28	300	69.50	1273	1272	1135	1.06	1.00	11.35	0.50	0.41	0.63
CD-29	305	71.25	560	534	496	0.47	0.42	4.96	0.22	0.17	0.28
CD-30	300	74.00	153	188	158	0.13	0.15	1.58	0.06	0.06	0.09

NOTES:

a. Testing in accordance with ASTM C593 (mainly Section 7). Average of 3 cubes.

b. Flow to be in 65 to 75 range.

c. 7 days at 130±3°F, closed vapor oven.

d. 7 days at 130±3°F, closed vapor oven followed by 21 days at 73±3°F, 95 to 100 percent relative humidity.

e. 28 days at 73±3°F, 95 to 100 percent relative humidity.

f. Pozzolanic index control: Calcitic hydrated lime - FA-16 - Silica sand (FA-16 Mix from Table 17); 7 day accelerated = 1201 psi, 28 day accelerated = 1273 psi, 28 day ambient = 100 psi.

g. Hydraulic index control: Type 1 portland cement - FA-16 - Silica sand (PC-1 Mix from Table 17); 7 day accelerated = 2250 psi, 28 day accelerated = 3100 psi, 28 day ambient = 1800 psi.

h. Crushed to passing #50 mesh.

1 lb./in.^{2} = .0703 kg/cm^2

Table 12

LIME KILN DUST - FLY ASH (FA-16) - SILICA SAND MORTAR CUBES[a]

COMPRESSIVE STRENGTH DEVELOPMENT AND COMPARISONS

LD (180 g) - FA-16 (360 g) - SAND (1480 g) - WATER (TO MEET FLOW)

LIME KILN DUST	WATER USED mℓ	FLOW[b]	7 DAY[c] ACC STRENGTH psi	28 DAY[e] ACC STRENGTH psi	28 DAY[e] AMB STRENGTH psi	7 DAY ACC POZ[f] CONT	28 DAY ACC POZ[f] CONT	28 DAY AMB POZ[f] CONT	7 DAY ACC HYD[g] CONT	28 DAY ACC HYD[g] CONT	28 DAY AMB HYD[g] CONT
LD-1	300[h]	72.00	566	545	336	0.47	0.43	3.36	0.22	0.18	0.19
LD-2	290[h]	70.75	238	246	194	0.20	0.19	1.94	0.09	0.08	0.11
LD-3	295[i,j]	69.75	1863	1763	851	1.55	1.38	8.51	0.73	0.57	0.47
LD-4	275[h]	68.75	425	511	309	0.35	0.40	3.09	0.17	0.16	0.17
LD-5	305[i,k]	68.75	896	1066	155	0.75	0.84	1.55	0.35	0.34	0.09
LD-6	305[h]	70.00	516	596	63	0.43	0.47	0.63	0.20	0.19	0.04
LD-7	315[i,j]	66.00	867	891	267	0.72	0.70	2.67	0.34	0.29	0.15
LD-8	NOT TESTED										
LD-9	NOT TESTED										
LD-10	300[h]	65.00	384	344	253	0.32	0.27	2.53	0.15	0.11	0.14
LD-11	310[h,k]	66.50	1039	1165	325	0.87	0.92	3.25	0.41	0.38	0.18
LD-12	310[h]	69.25	98	131	81	0.08	0.10	0.81	0.04	0.04	0.05

NOTES

a. Testing in accordance with ASTM C593 (mainly Section 7). Average 3 cubes.

b. Blow to be in 65 to 75 range.

c. 7 days at 130±3°F, closed vapor oven.

d. 7 days at 130±3°F, closed vapor oven followed by 21 days at 73±3°F, 95 to 100 percent relative humidity

e. 28 days at 73±3°F, 95 to 100 percent relative humidity.

f. Pozzolanic index control: Calitic hydrated lime - FA-16 - Silica sand (FA-16 Mix from Table 17); 7 day accelerated = 1201 psi, 28 day accelerated = 1273 psi, 28 day ambient = 100 psi.

g. Hydraulic index control: Type 1 portland cement - FA-16 - Silica sand (PC-1 Mix from Table 17); 7 day accelerated = 2550 psi, 28 day accelerated = 3100 psi, 28 day ambient = 1800 psi.

h. Significant bleeding.

i. Some bleeding.

j. 15 percent water required to slake lime kiln dust during initial mixing.

k. 25 percent water required to slake lime kiln dust during initial mixing.

1 lb./in.^{2} = .0703 kg/cm^2

Table 13

FLY ASH - CALCITIC HYDRATED LIME - SILICA SAND MORTAR CUBES[a] AND MISCELLANEOUS MATERIALS

COMPRESSIVE STRENGTH DEVELOPMENT AND COMPARISONS

FLY ASH (369 g) - CALCITIC HYDRATED LIME (180 g) - SAND (1480 g) - WATER (TO MEET FLOW)

FLY ASH	WATER USED mℓ	FLOW[b]	7 DAY[c] ACC STRENGTH psi	28 DAY[d] ACC STRENGTH psi	28 DAY[e] AMB STRENGTH psi	7 DAY ACC POZ[f] CONT	28 DAY ACC POZ[f] CONT	28 DAY AMB POZ[f] CONT	7 DAY ACC HYD[g] CONT	28 DAY ACC HYD[g] CONT	28 DAY AMB HYD[g] CONT
FA-1	340	71.25	550	685	418	0.46	0.54	4.18	0.22	0.22	0.23
FA-2	355	68.50	1500	1725	312	1.25	1.36	3.12	0.59	0.56	0.17
FA-3	350	67.00	980	1261	150	0.82	0.99	1.50	0.38	0.41	0.08
FA-4	350	74.75	1119	1192	217	0.93	0.94	2.17	0.44	0.38	0.12
FA-5	335	71.25	1106	1205	193	0.93	0.95	1.93	0.43	0.39	0.11
FA-6	NOT TESTED										
FA-7	350	72.75	1137	1187	146	0.95	0.93	1.46	0.45	0.38	0.08
FA-8	350	66.25	893	1118	93	0.74	0.88	0.93	0.35	0.36	0.05
FA-9	330	74.25	1181	1323	119	0.98	1.04	1.19	0.46	0.43	0.07
FA-10	350	73.75	678	790	505	0.56	0.62	5.05	0.27	0.25	0.28
FA-11	340	73.25	910	1043	176	0.76	0.82	1.76	0.36	0.34	0.10
FA-12	462	66.00	1055	1178	315	0.88	0.93	3.15	0.41	0.38	0.18
FA-13	360	67.75	1011	1119	90	0.84	0.88	0.90	0.40	0.36	0.05
FA-14	375	69.00	596	830	143	0.50	0.65	1.43	0.23	0.27	0.08
FA-15	350	72.00	908	1103	192	0.76	0.87	1.92	0.36	0.36	0.11
FA-16	360	69.25	1201	1273	100	1.00	1.00	1.00	0.47	0.41	0.06
FA-17	350	68.75	932	947	89	0.78	0.74	0.89	0.37	0.31	0.05
FA-18	375	74.75	1132		212	0.94	0.88	2.12	0.44	0.36	0.12
FA-19	400	66.50	1149	1083	166	0.96	0.85	1.66	0.45	0.35	0.09
Dolomitic Hydrated Lime	360	69.75	564	685	97	0.47	0.54	0.97	0.22	0.22	0.05
PC-1[i]	300	73.00	2550	3100	1800	2.12	2.44	18.00	1.00	1.00	1.00
STN-1[j]	285	71.50	77	64	28	0.06	0.05	0.28	0.03	0.02	0.02

NOTES: See attached sheet

Table 13 - Cont.

FLY ASH - CALCITIC HYDRATED LIME - SILICA SAND MORTAR CUBES[a] AND MISCELLANEOUS MATERIALS

COMPRESSIVE STRENGTH DEVELOPMENT AND COMPARISONS

FLY ASH (369 g) - CALCITIC HYDRATED LIME (180 g) - SAND (1480 g) - WATER (TO MEET FLOW)

NOTES:

a. Testing in accordance with ASTM C593 (mainly Section 7). Average 3 cubes.

b. Flow to be in 65 to 75 range.

c. 7 days at 130±3°F, closed vapor oven.

d. 7 days at 130±3°F, closed vapor oven followed by 21 days at 73±3°F, 95 to 100 percent relative humidity.

e. 28 days at 73±3°F, 95 to 100 percent relative humidity.

f. Pozzolanic index control: Calcitic hydrated lime - FA-16 - Silica sand (FA-16 Mix in table); 7 day accelerated = 1201 psi, 28 day accelerated = 1273 psi, 28 day ambient = 100 psi.

g. Hydraulic index control: Type 1 portland cement - FA-16 - Silica sand (PC-1 Mix in table); 7 day accelerated = 2250 psi, 28 day accelerated = 3100 psi, 28 day ambient = 1800 psi.

h. Dolomitic hydrated lime (180 g) - FA-16 (360 g) - Sand (1480 g) - Water (to meet flow).

i. Type 1 portland cement (180 g) - FA-16 (360 g) - Sand (1480 g) - Water (to meet flow).

j. STN-1 (180 g) - FA-16 (360 g) - Sand (1480 g) - Water (to meet flow).

1 lb./in.^{2} = .0703 kg/cm^2

5.6 Evaluation of Kiln Dust Composition

5.6.1 Comparison of Composite and Daily Grab Samples

Of the 45 kiln dust samples received, a complete compositional analysis of individual daily grab samples was provided by ten of the dust suppliers (9 cement plants and 1 lime plant). Each of these analyses was compared with the analysis of the corresponding composite after blending of the individual daily grab samples, as reported in the previous section. The oxide analyses usually involved nine elements, including loss on ignition.

When comparing the analysis of individual daily grab samples with the analysis of the composite sample from the same plant, certain values from composite analyses fell outside the range reported by producers for daily grab samples. These variations occurred in less than 20 percent of all the cement dust analyses. In most instances, the variation fell within 10 to 15 percent of the upper or lower range reported in the individual sample analyses. Most of the differences were noted in two cement dust samples. At four other cement plants, the composite analysis for all nine elements were all within the range reported by the producer for the individual daily grab samples.

Only one set of analyses of individual daily grab samples was received from a lime producer. For that sample, the composite analysis fell outside the limits of the daily grab samples for three of nine elements. The average variation was approximately 15 percent less than the lower limits for these three elements.

Initially, it was believed that there would be significant variations in the composition of kiln dust from the same plant on a day-to-day basis, even during normal operating periods. However, of the ten sets of analyses of individual daily grab samples that were received, less than 20 percent of all values showed a variation greater than 10 percent over the 15-day sampling period. At three of the ten sampling locations, the analyses of all elements for the individual daily grab samples were within a 10 percent variation throughout the sampling period. For example, the CaO content of the individual grab samples from one cement plant ranged from 40.58 to 44.74 percent. These data indicate that the composition of kiln dust during normal kiln operating periods is relatively uniform, more so than was originally expected.

5.6.2 Comparison of Fresh and Stockpiled Samples

From the chemical analyses of kiln dust samples shown in Tables 8 and 9, it is evident that there is virtually no free lime whatsoever in stockpiled kiln dusts due to hydration and/or carbonation resulting from prolonged exposure to the elements. In addition to stockpiling, conditioning of fresh, dry kiln dust with water to retard dusting will hydrate the free lime in the dust and will, in effect, result in kiln dust with physical and chemical characteristics quite similar to those of stockpiled dusts. Because of the negligible presence of free lime in stockpiled and conditioned dusts, such materials are probably not very reactive with fly ash. Because of the possibility of carbonation, all kiln dust samples (including stockpiled and conditioned dusts) were kept sealed in their respective containers when not used to prevent decreased reactivity due to carbonation of free lime.

5.7 Classification of Kiln Dusts

Results of the characterization testing were used in conjunction with information regarding the source of the kiln dusts in order to develop a system for classification of the kiln dusts. Because of differences between cement and lime kiln dusts, a separate means of classifying each type of dust is discussed.

5.7.1 Cement Kiln Dusts

The most obvious indicators for classification of cement kiln dusts are the kiln process and degree of separation in the dust collection system. There are two types of cement kiln process (dry and wet) and in each of these processes the dust collected may be separated for partial return to the kiln or simply collected in total for recycling or disposal.

Therefore, there are four possible groupings of cement kiln dust:

Group I - Dry Process-Total Collection
Group II - Dry Process-Separation
Group III - Wet Process-Total Collection
Group IV - Wet Process-Separation.

For all cement kiln dust samples obtained for this program, information was obtained from the respective cement companies concerning the type of kiln process, the nature of the dust collection system at the plant, the point within the collection system where the dust sample was obtained, and whether or not any dust separation is practiced at that plant. Where possible, a schematic diagram of the dust collection system was obtained. Of the 30 cement plants included in the sampling program, 18 submitted a schematic diagram. For the remaining plants, details of the dust collection system and the type of dust sample obtained were discussed by telephone with operations personnel at each plant.

All 33 cement kiln dust samples were placed into their proper groupings. The grouping of these samples is as follows:

Group I - 7 samples (CD-11, CD-19, CD-20, CD-23, CD-26, CD-28, CD-30)
Group II - 5 samples (CD-1, CD-10, CD-12, CD-25, CD-32)
Group III - 7 samples (CD-5, CD-7, CD-8, CD-13, CD-17, CD-22, CD-29)
Group IV - 14 samples (CD-2, CD-3, CD-4, CD-6, CD-9, CD-14, CD-15, CD-16, CD-18, CD-21, CD-24, CD-27, CD-31, CD-33).

Because the composition of kiln dust varies depending on the location within the system that the dust is collected, there are often significant differences between total and separated dusts. Normally, the CaO content is higher in the coarser particles which are captured by cyclones (when used) or in the forward compartments of precipitators. The finer dust particles usually have a higher concentration of sulfates and alkalis, while SiO_2,

Al_2O_3, Fe_2O_3 and MgO contents tend to be fairly equally distributed in all sizes.(27) Therefore, most total dusts are generally higher in free lime content than separated dusts, while most separated dusts are higher in alkali and sulfate than total dusts.

In wet process kilns, the rate of dust generation is slightly less than for a dry system, since a portion of the wet kiln is used for drying the slurry. Hence, somewhat less calcium would normally be present in the dust from wet process kilns, meaning that, in general, dry process kiln dust may be a somewhat more desirable product. Most dry systems utilize baghouse collections instead of precipitators and the properties of the dust should not be as variable between compartments of a baghouse as between the stages of an electrostatic precipitator. However, with baghouses, more SO_2 is removed than in precipitators, resulting in comparatively higher sulfate levels.

5.7.2 Lime Kiln Dusts

Since lime kiln dusts are not usually recycled, the major differences in such dusts are the reactivity, which is directly related to free calcium (and possibly magnesium) oxide content. A simple temperature rise test was performed to evaluate the potential reactivity of the lime kiln dusts. The test consisted of adding 100 milliliters of water to 500 grams of lime kiln dust and measuring the temperature rise of the mixture until it returned to ambient temperature. Lime kiln dusts with a high free lime content produced an exothermic reaction upon addition of water due to the slaking of the calcium oxide. The higher the temperature rise, the more reactive the lime dust.

Based on the chemical analysis and the results of the temperature rise test, lime kiln dusts may be grouped as follows:

Group H - Dusts with High Reactivity
Group L - Groups with Low Reactivity.

A temperature rise of 20°C. (68°F.) was selected as the criteria for identifying the extent of lime kiln dust reactivity. Of the 12 lime kiln dusts in the study, six are considered Group H dusts. None of these six reactive dusts is dolomitic. The grouping of lime kiln dusts according to temperature rise is as follows:

Group H - 6 samples (LD-3, LD-5, LD-6, LD-7, LD-9, LD-11)
Group L - 6 samples (LD-1, LD-2, LD-4, LD-8, LD-10, LD-12).

Once free lime (CaO) is slaked, it converts to calcium hydroxide or $Ca(OH)_2$, hydrated lime. Sometimes, when the slaking reaction is concluded, much of the reactivity of the original material has dissipated. Some hydrated materials are able to develop only a fraction of the strength they had been capable of in the unhydrated state. An additive (such as lime slurry) can be added to accelerate strength development in such cases.(28)

5.8 Classification of Fly Ashes

A general classification system for fly ashes was presented in a recent publication concerning the use of brown coal fly ashes in road base courses. (29) The fly ashes in this classification system were divided in the following four groupings, based principally on chemical composition:

Group I - Alumina-Silica Fly Ashes - having a percentage of SiO_2 to Al_2O_3 of 2:1 or greater and a CaO content less than 15 percent.

Group II - Silica-Alumina Fly Ashes - having a percentage of SiO_2 to Al_2O_3 of less than 2:1, a CaO content of less than 15 percent, and SO_3 content of less than 3 percent.

Group III - Sulfate-Calcium Fly Ashes - having a total CaO content greater than 15 percent and SO_3 content exceeding 3 percent.

Group IV - High Calcium-Low Sulfate Fly Ash - having a total CaO content greater than 15 percent and SO_3 content less than 3 percent.

Considering particle size distribution and specific surface or Blaine fineness, fly ashes are physically classified as:

Fine-grained - Greater than 75 percent finer than .071 mm (approximately 200 mesh) and with a specific surface (Blaine fineness) greater than 3,000 cm^2/g.

Medium-grained - Between 40 and 75 percent finer than .071 mm and with a specific surface from 1,500 to 3,000 cm^2/g.

Coarse-grained - Less than 40 percent finer than .071 mm and with a specific surface less than 1,500 cm^2/g.

Fly ashes can be further classified in terms of their pozzolanic activity. To a large extent, pozzolanic activity is related to the CaO content of the fly ash. The reactivity of fly ashes from Groups I and II are normally quite low because most Class F or bituminous coal fly ashes, which would mainly comprise these groups, are low in CaO content. On the other hand, most Class C fly ashes, which would usually fall into Groups III or IV, are characterized by a fairly high CaO content.

Fly ashes, in terms of pozzolanic activity, are classified according to CaO content as follows:

Very weakly active - CaO content less than 3.5 percent.
Weakly active - CaO content from 3.5 to 7 percent.
Active - CaO content from 7 to 14 percent.
Highly active - CaO content greater than 14 percent.(29)

The overall groupings of these fly ash samples are as follows:

Group I - 7 samples (FA-2, FA-4, FA-6, FA-7, FA-9, FA-13, FA-17).
Group II - 7 samples (FA-3, FA-5, FA-8, FA-14, FA-15, FA-16, FA18).
Group III - 2 samples (FA-10, FA-12)
Group IV - 2 samples (FA-1, FA-11).

5.9 Characterization of Aggregate Samples

Each of the six aggregate samples used in the Task C and Task D phases of the testing was first analyzed to determine its particle size distribution. The resultant gradation of each aggregate sample was then compared with the recommended gradation limits for highway bases and subbases, as presented in ASTM D2940 (30) and shown on the gradation curve in Figure 6. Figure 7 shows the gradation of the limestone aggregates compared to the ASTM limits. Figure 8 shows a similar comparison for the siliceous aggregates. Figure 9 shows the gradation of the slag and the granitic gneiss.

In addition to particle size distribution, other engineering properties of each aggregate were also determined. These included specific gravity, Los Angeles abrasion loss, and sodium sulfate soundness. Available producer data was used whenever provided. Laboratory testing was performed to determine engineering properties in those instances where no producer data was furnished. Table 14 presents a summary of the engineering properties of each of the six aggregate samples.

From a review of Table 14 and the particle size distribution curves for each of the six aggregates, it is evident that some aggregate samples conform more closely to the ASTM gradation specifications than others. The particle size distribution of the calcitic limestone, granitic gneiss, and blast furnace slag aggregates is essentially within the specification limits. The particle size distribution of the dolomitic limestone is well graded, but slightly finer than the ASTM limits. The siliceous sand and gravel aggregate is somewhat skip graded, having somewhat too much material between the 25 mm (1 inch) and 12.7 mm (1/2 inch) sizes and being a bit bony or deficient in fine material between the 12.7 mm (1/2 inch) and 6.35 mm (1/4 inch) and between the 50 and 200 mesh sizes. The river sand is obviously much finer than the ASTM gradation range.

Although the gradation of the river sand is finer than the ASTM base and subbase aggregate gradation, it does generally conform to the suggested gradation limits for aggregate used in cement-treated aggregate base, as recommended by the Portland Cement Association.(31) In order to achieve the most economical cement factor in cement-treated aggregate base, a minimum of 55 percent by weight of an aggregate should be finer than a No. 4 sieve, with a maximum of 90 percent. The river sand, with 88 percent passing the No. 4 sieve, is the only aggregate sample meeting these requirements.

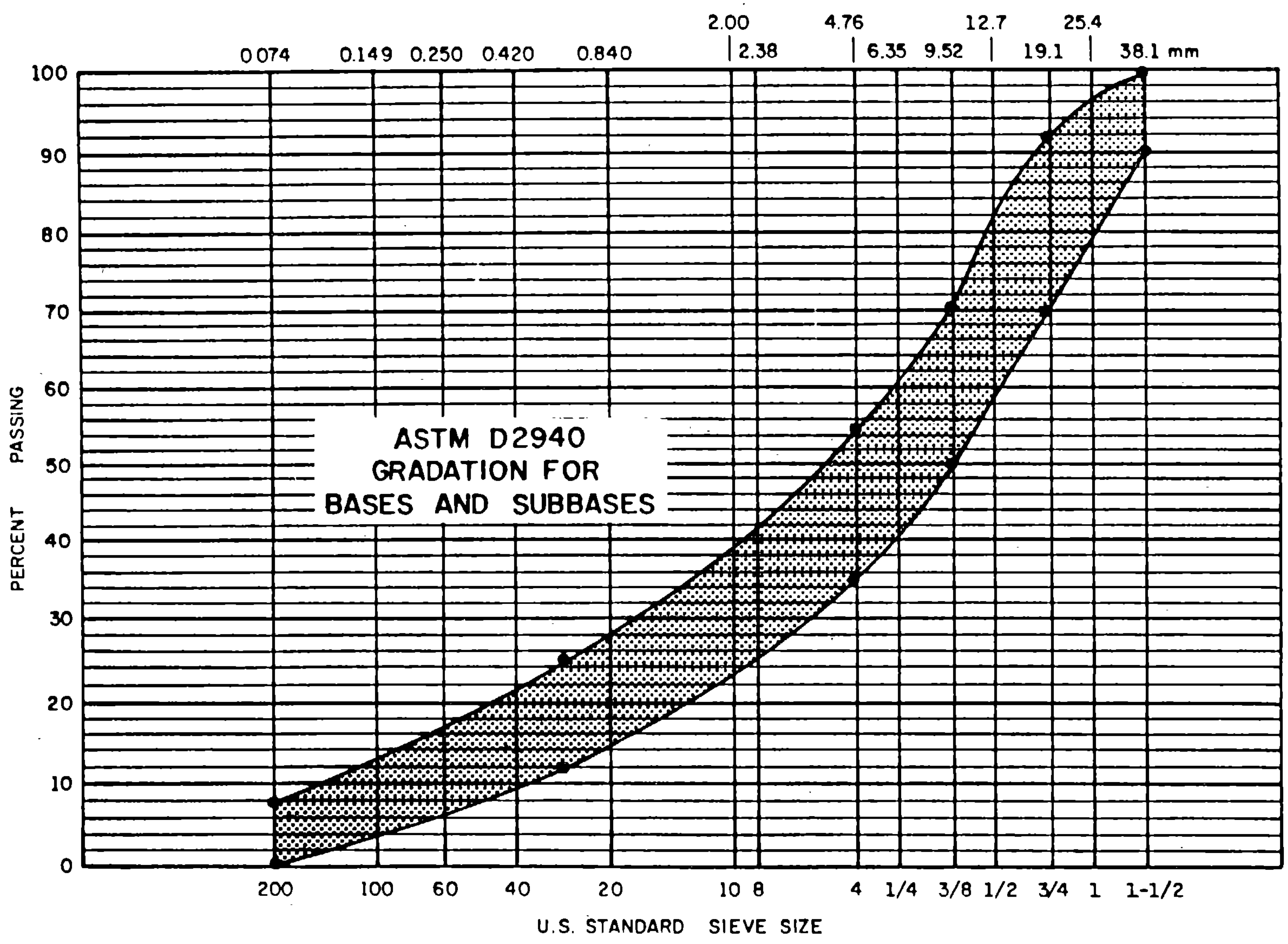


FIGURE 6

ASTM GRADATION RANGE OF GRADED AGGREGATE MATERIAL FOR HIGHWAY BASES AND SUBBASES

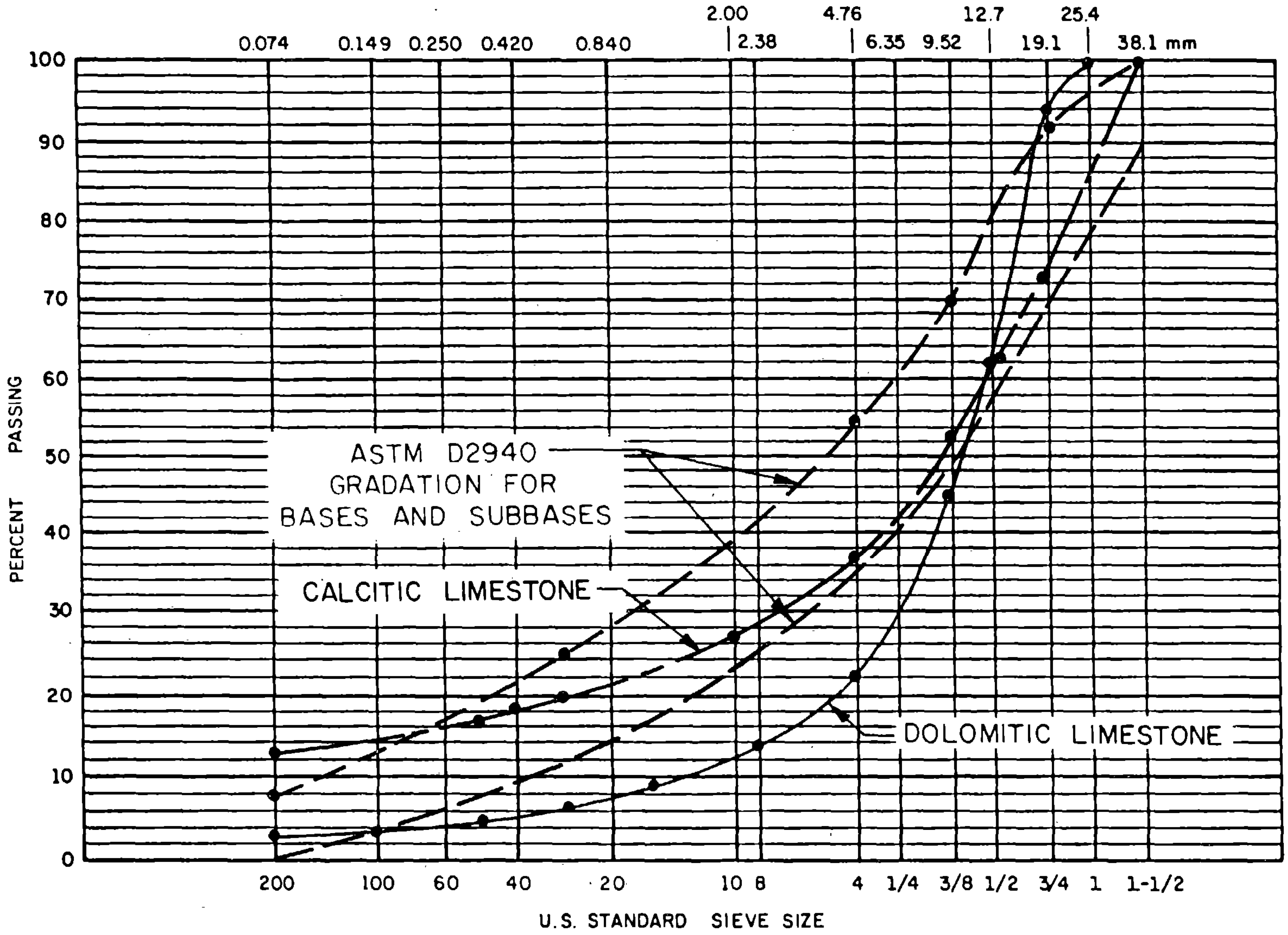


FIGURE 7

PARTICLE SIZE DISTRIBUTION OF DOLOMITIC AND CALCITIC LIMESTONE AGGREGATES

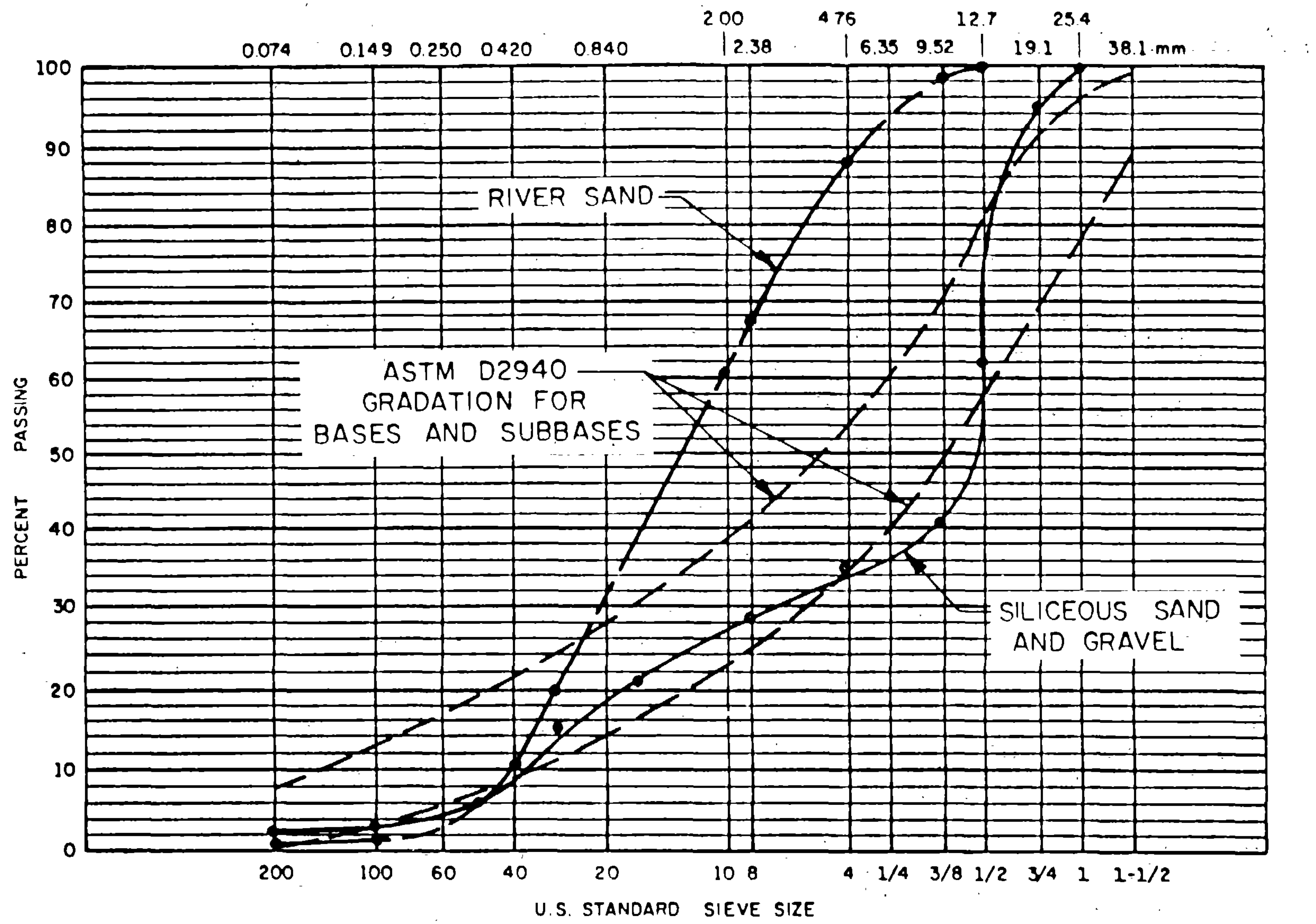


FIGURE 8

PARTICLE SIZE DISTRIBUTION OF SILICEOUS SAND AND GRAVEL, AND RIVER SAND AGGREGATES

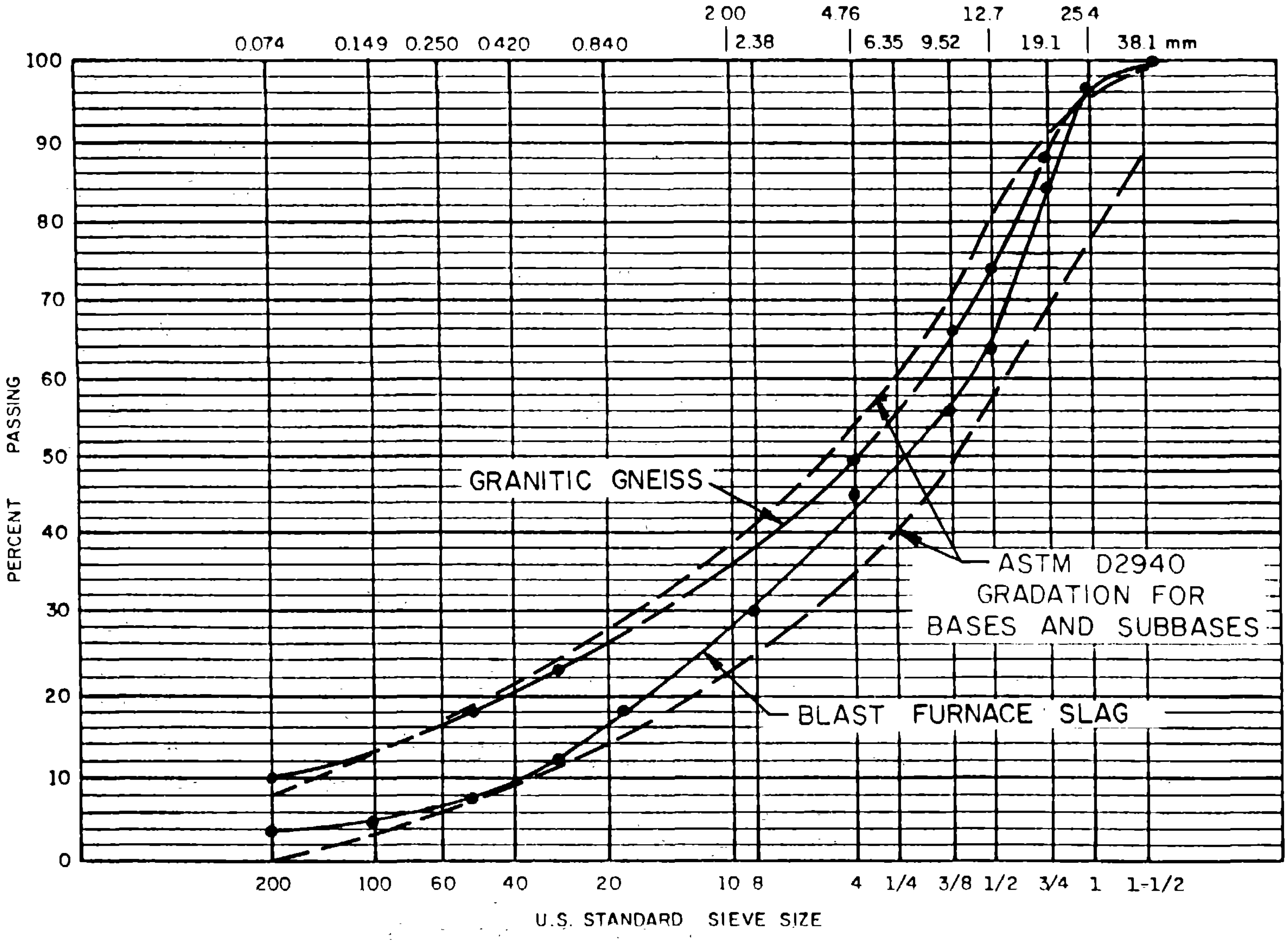


FIGURE 9

PARTICLE SIZE DISTRIBUTION OF GRANITIC GNEISS AND BLAST FURNACE SLAG AGGREGATES

Table 14

ENGINEERING PROPERTIES OF AGGREGATE SAMPLES

Aggregate Code Letter	Aggregate Type	Specific Gravity	Particle Size Distribution (Percent Passing) 1-1/2"	3/4"	1/2"	#4	#30	#200	Los Angeles Abrasion Loss*	Sodium Sulfate Soundness Loss*
A	Dolomitic Limestone	2.84	100.0	94.0	62.0	22.2	6.5	2.7	28.5	1.0
B	Granitic Gneiss	2.90	100.0	88.0	73.3	49.2	23.0	10.0	20.0	1.0
C	Blast Furnace Slag (Air Cooled)	2.55	99.6	83.8	63.4	45.2	12.9	4.0	34.5	4.5
D	Siliceous Sand and Gravel	2.65	100.0	95.2	61.6	35.4	14.9	2.5	27.5	3.9
E	Calcitic Limestone	2.56	100.0	73.5	62.8	37.6	20.4	13.3	32.5	2.5**
F	River Sand	2.57	100.0	100.0	100.0	88.4	20.0	1.3	35.0	2.0

*Expressed as a percentage

**Test run using magnesium sulfate.

NOTE: 1 inch = 25.4 mm.

6. DETERMINATION OF OPTIMUM KILN DUST-FLY ASH RATIOS

6.1 Purpose of Tests

The kiln dust samples analyzed during the characterization testing phase were evaluated in Task B to determine optimum kiln dust-fly ash ratios for each sample. Optimum kiln dust-fly ash combinations were determined on the basis of the strength development of test cylinders which were molded and cured under prescribed standard conditions. The strength test results were used to identify optimum strength proportions for different kiln dust and fly ash combinations. The strength values developed during this phase were used as an indication of which kiln dusts would be best suited for further evaluation in Task C. Where possible, kiln dust-fly ash strength development was correlated with key physical or chemical properties of kiln dust samples.

6.2 Description of Test Methods

The tests used in this phase of Task B were intended to complement the ASTM pozzolanic activity tests performed during the characterization testing phase. The pozzolanic activity tests were performed on 51 mm (2 inch) cube specimens in which the materials were lightly tamped into the cube molds in accordance with ASTM C109. For this phase of the testing program, cylindrical test specimens were prepared and tested at or near maximum dry density. To conserve sample materials, small size cylinder specimens were prepared in a Carver laboratory press mold 28.6 mm (1-1/8 inch) in diameter. All test specimens were compressed rather than compacted, using a standard procedure developed after a number of trials to simulate the maximum compacted dry density of Proctor size specimens. Molded densities of Carver press specimens ranged from 95 to 110 percent of Proctor densities, with an average of 100 percent.

All test specimens were prepared by first mixing the desired proportions of dry kiln dust and fly ash in a plastic bag, adding the required water corresponding to optimum moisture content, and kneading the ingredients by hand for approximately two to three minutes until thoroughly mixed. Test specimens were molded in the Carver press at or near optimum moisture content and cured for 7 days at 38°C. (100°F.). The cured specimens were then tested for compressive strength in a testing machine in accordance with ASTM C39. In this phase of the program, control mixes and kiln dust-fly ash test mixes were prepared.

6.3 Preparation and Testing of Control Mixes

6.3.1 Kiln Dust-Fly Ash Control Mixes

Control mixes were initially prepared by combining each kiln dust sample with a control fly ash. A typical Class F bituminous coal fly ash (FA-16) was selected as the control fly ash for these tests. For the kiln dust-fly ash control mix tests, the mix proportions used were 2 parts, by weight, dust to 1 part control fly ash for all cement kiln dusts and 1 part, by weight, dust to 1 part control fly ash for all lime kiln dusts. These proportions were used because lime kiln dusts generally have higher concentrations of free lime than cement kiln dusts.

When reactive (Group H) lime kiln dusts were mixed with water, a hydration or slaking of the free lime occurred. The amount of slaking water required for complete hydration of the free lime, normally ranged from 15 to 25 percent by weight of the dust. Once the temperature of the reactive dust had returned to normal, the conditioned dust was then sealed in a plastic bag to maintain moisture equilibrium for at least 24 to 48 hours prior to subsequent mixing with the fly ash and molding of test specimens.

An effective way of compensating for reduced strength development following hydration of the free lime component in lime kiln dust is to add some kind of an activator such as a caustic material (like calcium or sodium hydroxide), during mixing with the fly ash and aggregate. Although this approach has been successful in previous laboratory and field tests (32), no such caustic additives were used in this program. The scope of laboratory testing work in this investigation was confined to using dry kiln dusts without conditioning or the addition of any chemical activators.

The results of the 7-day strength tests for cement kiln dust-fly ash control mixes using the FA-16 control fly ash are presented in Table 15. Similar results for lime kiln dust-fly ash control mixes are presented in Table 16. Numbers in parentheses after the strength values indicate the ranking of strength for all cement kiln dust and lime kiln dust samples. These results are compared with the 7-day strength (545 psi) of a reference mix using high calcium hydrated lime and FA-16 fly ash. In most instances, the kiln dust-fly ash mixes resulted in improved strength compared to the reference mix.

6.3.2 Kiln Dust-Fly Ash-Aggregate Control Mixes

Control mix tests following these procedures were also performed on combinations of kiln dust, fly ash, and aggregate using FA-16 as the control fly ash and standard Ottawa sand (ASTM C109) as the aggregate in Carver press test specimens. The aggregate percentage was held at 76 percent by weight of the total mix, which corresponds to the percentage of aggregate used in all of the pozzolanic activity tests. The paste portion of the mix consisted of 2 parts, by weight, dust to 1 part control fly ash for all cement kiln dusts and 1 part, by weight, dust to 1 part control fly ash for all lime kiln dusts.

The results of the 7-day strength tests for all cement kiln dust-fly ash-aggregate control mixes using Ottawa sand and the FA-16 control fly ash are presented in Table 15. Similar results for lime kiln dust-fly ash control mixes are presented in Table 16. Numbers in parentheses after the strength values indicate the ranking of strength for all cement kiln dust and lime kiln dust samples. These results are also compared with the 7-day strength (126 psi) of a reference mix using Ottawa sand with high calcium hydrated lime and FA-16 fly ash. In virtually all cases, the kiln dust mix strengths were significantly higher than the reference mix strength.

Table 15

RESULTS OF KILN DUST-FLY ASH AND KILN DUST-FLY ASH-SAND REFERENCE MIX STRENGTH TESTS USING CEMENT KILN DUSTS

	KILN DUST-FLY ASH		KILN DUST-FLY ASH-SAND	
Kiln Dust No.	7-Day Compressive Strength	Ratio of KD-FA Reference Mix Strength	7-Day Compressive Strength	Ratio of KD-FA-Sand Reference Mix Strength
CD-1	1668 (11)	3.06	503 (14)	3.99
CD-2	1289 (18)	2.37	495 (15)	3.93
CD-3	1911 (9)	3.51	520 (11)	4.13
CD-4	1245 (20)	2.28	260 (23)	2.06
CD-5	1266 (19)	2.32	168 (29)	1.33
CD-6	1458 (14)	2.68	235 (25)	1.87
CD-7	1314 (17)	2.41	360 (18)	2.86
CD-8	2056 (5)	3.77	511 (12)	4.06
CD-9	1593 (12)	2.92	939 (1)	7.45
CD-10	1729 (10)	3.17	629 (7)	4.99
CD-11	1551 (13)	2.85	486 (16)	3.86
CD-12	1107 (22)	2.03	233 (26)	1.85
CD-13	184 (32)	0.34	335 (19)	2.66
CD-14	1978 (7)	3.63	277 (22)	2.20
CD-15	277 (30)	0.51	67 (30)	0.53
CD-16	2389 (3)	4.38	578 (8)	4.59
CD-17	2113 (4)	3.88	704 (4)	5.59
CD-18	1936 (8)	3.55	755 (2)	5.99
CD-19	1358 (15)	2.49	511 (13)	4.06
CD-20	1157 (21)	2.12	687 (5)	5.45
CD-21	235 (31)	0.43	444 (17)	3.52
CD-22	662 (25)	1.21	50 (32)	0.40
CD-23*	503 (27)	0.92	50 (33)	0.40
CD-24	50 (33)	0.09	243 (24)	1.93
CD-25	981 (23)	1.80	209 (28)	1.66
CD-26*	855 (24)	1.57	302 (20)	2.40
CD-27	2038 (6)	3.74	738 (3)	5.86
CD-28	2682 (1)	4.92	671 (6)	5.33
CD-29	520 (26)	0.95	537 (10)	4.26
CD-30	2666 (2)	4.89	553 (9)	4.39
CD-31*	1358 (16)	2.49	218 (27)	1.73
CD-32	472 (28)	0.87	294 (21)	2.33
CD-33	459 (29)	0.84	58 (31)	0.46

*Stockpiled kiln dust samples. 1 lb./in.^{2} = .0703 kg/cm^2

NOTE: Reference mix No. 1 (20 percent high calcium hydrated lime to 80 percent FA-16) had average 7-day compressive strength of 545 psi.

Reference mix No. 2 (4.8 percent high calcium hydrated lime, 19.2 percent FA-16, and 76 percent Ottawa sand aggregate) had an average 7-day compressive strength of 126 psi.

Table 16

RESULTS OF KILN DUST-FLY ASH AND KILN DUST-FLY ASH-SAND REFERENCE MIX STRENGTH TESTS USING LIME KILN DUSTS

	KILN DUST-FLY ASH		KILN DUST-FLY ASH-SAND	
Kiln Dust No.	7-Day Compressive Strength	Ratio of KD-FA Reference Mix Strength	7-Day Compressive Strength	Ratio of KD-FA-Sand Reference Mix Strength
LD-1	1115 (6)	2.05	319 (5)	2.53
LD-2	1140 (5)	2.09	176 (8)	1.40
LD-3	2549 (2)	4.68	830 (1)	6.59
LD-4	2750 (1)	5.05	679 (2)	5.39
LD-5	1056 (7)	1.94	58 (11)	0.46
LD-6	201 (11)	0.37	101 (10)	0.80
LD-7	218 (10)	0.40	50 (12)	0.40
LD-8*	1333 (4)	2.45	235 (7)	1.87
LD-9	1962 (3)	3.60	495 (4)	3.93
LD-10	880 (9)	1.61	258 (6)	2.05
LD-11	101 (12)	0.19	553 (3)	4.39
LD-12	964 (8)	1.77	109 (9)	0.87

*Stockpiled kiln dust sample.

NOTE: Reference mix No. 1 (20 percent high calcium hydrated lime to 80 percent FA-16) had an average 7-day compressive strength of 545 psi.

Reference mix No. 2 (4.8 percent high calcium hydrated lime, 19.2 percent FA-16, and 76 percent Ottawa sand aggregate) had an average 7-day compressive strength of 126 psi.

Strength values given in psi   1 lb./in.^{2} = .0703 kg/cm^2

6.3.3 Fly Ash Control Mixes

Fly ash control mixes were also prepared using standard procedures in order to evaluate the relative pozzolanic strength development potential of each of the 18 fly ash samples in the testing program. The lime-fly ash control mixes contained either 1 part high calcium hydrated lime and 2 parts fly ash or 1 part high calcium hydrated lime and 4 parts fly ash. None of these control mixes contained sand aggregate.

A total of three test specimens were made for each lime-fly ash control mix. The 1:2 control mixes were cured for 7 days at 38°C. (100°F.). Many of these specimens developed extremely high compressive strength (approaching or in excess of 3000 psi), particularly those mixes containing Class C fly ash. It was, therefore, decided to also prepare 1:4 control mixes, but to modify curing conditions to 14 days at 23°C. (73°F.) in order to more closely simulate field curing.

A total of 14 of the 18 fly ash samples were further evaluated in the second lime-fly ash control mixes. These 14 samples were selected on the basis of representing those fly ashes which would most likely be included in the later stages of the testing program for geographical reasons.

Table 17 presents the results of the lime-fly ash control mix strength tests for both the 1:2 and 1:4 mix proportions. Numbers in parentheses after the strength values indicate the ranking of strength for all fly ash samples, although four of the fly ash samples were not evaluated using 1:4 mix proportions. From these data, it is evident that significantly greater strength development was observed from control mixes containing Class C (lignite or sub-bituminous coal) fly ashes.

6.4 Preparation and Testing of Kiln Dust-Fly Ash Test Mixes

A series of Carver press specimens were prepared and tested to determine optimum kiln dust-fly ash ratios for a wide variety of material combinations. Test specimens were cylinders prepared using the Carver press. The test specimens contained only kiln dust and fly ash with no sand aggregate. The respective dust and fly ash combinations were blended together in various proportions so that the reaction between the two materials could be evaluated without any reduction of strength values due to the addition of aggregate.

Instead of selecting kiln dusts with a number of different properties and blending these with fly ashes also having a number of different properties, it was decided to combine kiln dust and fly ash samples that exist in reasonable geographical proximity. The advantages to this approach were:

1. Data would be developed for combinations of materials which have a reasonable expectation of being used together in a future field demonstration project.

Table 17

RESULTS OF LIME-FLY ASH CONTROL MIX STRENGTH TESTS

		Compressive Strength (psi)	
Fly Ash Number	Fly Ash Group	1 Lime:2 Fly Ash 7 Days - 38°C. (100°F.)	1 Lime:4 Fly Ash 14 Days - 23°C. (73°F.)
FA-1*	IV	3789 (4)	N.T.
FA-2*	I	4259 (3)	1585 (5)
FA-3	II	2582 (11)	742 (9)
FA-4	I	3383 (6)	1754 (4)
FA-5	II	1275 (18)	459 (14)
FA-6	I	2985 (8)	N.T.
FA-7	I	2968 (9)	486 (13)
FA-8	II	2540 (12)	N.T.
FA-9*	I	5718 (1)	3605 (1)
FA-10*	III	5416 (2)	N.T.
FA-11*	IV	3789 (5)	2779 (2)
FA-12*	III	3068 (7)	2251 (3)
FA-13	I	1408 (17)	971 (8)
FA-14	II	2465 (13)	673 (10)
FA-15	II	2230 (14)	547 (12)
FA-16	II	1694 (15)	648 (11)
FA-17	I	2833 (10)	1075 (6)
FA-18	II	1503 (16)	1043 (7)

*Indicates Class C fly ash.
N.T. indicates no test performed.
1 lb./in.^{2} = .0703 kg/cm^2

2. Matching kiln dusts and fly ashes together based on geographical proximity introduced a random selection of material combinations and avoided a possible bias in selecting and combining materials with desired properties strictly on the basis of characterization test results.

3. Testing of certain combinations could proceed upon receipt of samples. This avoided delaying the kiln dust-fly ash testing until all samples were received and characterized and helped spread out the testing over a more reasonable time period.

In all, a total of 66 kiln dust-fly ash mixes were investigated in Task B. All 45 of the kiln dust samples and all 18 of the fly ash samples were included in these 66 mixes. Of the 66 kiln dust-fly ash mix combinations tested, 48 included cement kiln dust and 18 included lime kiln dust. Each of these mix combinations involved the preparation of Carver press test specimens at several different kiln dust-fly ash ratios. A minimum of three test specimens were prepared at each kiln dust-fly ash ratio. All test specimens were cured to 7 days at 38°C. (100°F.) and tested for compressive strength. The optimum kiln dust-fly ash ratio was determined based on mix proportions resulting in maximum 7-day compressive strength.

Of the 48 kiln dust-fly ash mixes containing cement kiln dust, 40 showed an increase in 7-day strength when using fly ash other than the control fly ash (FA-16). Some extremely high compressive strength values were observed in mixes using Class C fly ash.

Of the 18 kiln dust-fly ash mixes containing lime kiln dust, only 8 showed an increase in 7-day strength when using fly ash other than the control fly ash (FA-16). During the 7-day curing period, a number of the Group H (reactive) lime kiln dust test specimens exhibited signs of expansion and loss of strength. There were several instances in which significant strength gains (3000 psi or greater) were observed when lime kiln dusts were blended with Class C fly ashes. In such cases, the strength gain is probably attributable to the self-hardening characteristics of the fly ash, more so than the lime kiln dust. It has been shown that adequate mixing of such fly ashes with component materials and rapid compaction of the mixtures are important factors in attaining maximum strength development.(33)

As indicated previously, the handling of the Group H lime kiln dusts presented a problem. These dusts are highly reactive and are exothermic when exposed to water. The best way to handle such dusts is to proportion them as desired with fly ash in the dry, add an excess of water above that required for compaction, and compact the mixture as soon as it returns to room temperature. Even if handled in this manner, however, a number of mixtures with Group H lime kiln dusts showed expansive tendencies in the Carver mixes, probably because of the high degree of particle-to-particle contact in these specimens. This may or may not be a problem when aggregate is used. When mixing Group H lime kiln dusts (or high free lime cement kiln dusts), it is important to maintain a condition of excess moisture even though the moisture at molding may exceed the optimum value for density.

6.5 Discussion of Task B Test Results

6.5.1 Kiln Dust-Fly Ash Ratios

All 66 of the Task B test mixes involved preparation of test specimens at kiln dust-fly ash ratios of 2:1, 1:1, and 1:2. Selected test mixes were also evaluated at other kiln dust fly ash ratios (3:1, 3:2, 2:3, and 1:3) in order to more clearly define optimum mix proportions. Of the 48 cement kiln dust-fly ash mixes, 26 (or 54.2 percent) had an optimum kiln dust-fly ash ratio of 1:1. Most of the remaining cement kiln dust mixes had an optimum kiln dust-fly ash ratio of 2:1. Of the 18 lime kiln dust-fly ash mixes, the optimum kiln dust-fly ash ratio was nearly equally divided between 1:1 (38.9 percent) and 1:2 (33.3 percent).

6.5.2 Molded Densities of Task B Mixes

To attain maximum strength development in lime or cement stabilized compositions, it is generally necessary to compact the mixture to its maximum density, at or near the so-called optimum moisture content, as determined by a moisture-density (Proctor) test. A series of trials were performed to develop a molding procedure for Carver press specimens that would result in compressed specimens having densities as close as possible to the maximum densities obtained in Proctor testing. Molded densities for the kiln dust-fly ash Carver test specimens ranged from 1378 to 1762 kilograms per cubic meter (86 to 110 pounds per cubic foot).

A comparison was made of the molded Carver press densities and the maximum Proctor densities for 26 different kiln dust-fly ash mixes. The molded Carver densities ranged from 95 to 110 percent of the corresponding maximum Proctor densities with an average of 100 percent of Proctor density. From these comparisons, it is reasonable to conclude that the Carver specimens were molded to a density that is approximately the same as the Proctor density.

6.5.3 Comparison of Fresh vs. Stockpiled Kiln Dusts

In five of the kiln dust-fly ash test mixes, stockpiled kiln dust samples were substituted for fresh kiln dust samples obtained from the same source and the resultant mixes were cured and tested for compressive strength. The results of these tests are presented in Table 18. Several of the stockpiled kiln dust mixes exhibit strengths that are comparable to those of the fresh dust mixes. However, judgments concerning the relative suitability of stockpiled kiln dusts must also be based on the strength of such dusts in combination with fly ash and aggregate.

6.6 Correlation of Control Mix Strengths Data with Characterization Test Results

The prime purpose of this laboratory evaluation is to develop data on kiln dust properties and kiln dust-fly ash strength interactions that will

Table 18

COMPARISON OF COMPRESSIVE STRENGTH VALUES FOR TASK B MIXES WITH FRESH VS. STOCKPILED KILN DUST SAMPLES

Mix No.	Kiln Dust No.	Fly Ash No.	Kiln Dust-Fly Ash Ratio	Compressive Strength (psi) Fresh	Compressive Strength (psi) Stockpiled
4	CD-4 and CD-31*	FA-14	2:1	1593	1216
			1:1	805	823
			1:2	252	352
7	LD-2 and LD-8*	FA-7	2:1	629	704
			1:1	811	516
			1:2	860	444
36	CD-19 and CD-23*	FA-9	2:1	679	679
			1:1	444	649
			1:2	2138	585
64	CD-19 and CD-23*	FA-16	2:1	1366	265
			1:1	1597	151
			1:2	1383	95
65	CD-4 and CD-31*	FA-7	2:1	1308	1324
			1:1	868	989
			1:2	545	495

*Stockpiled kiln dust samples.

provide information needed to establish relationships between strength development and key composition parameters for a wide variety of kiln dusts. Such relationships would enable a supplier or prospective user of kiln dust to assess the quality of the material and be able to predict its compressive strength when combined with fly ash of known characteristics. The Task B strength parameters that appear to be most directly related to kiln dust and fly ash characteristics are the 7-day accelerated and the 28-day ambient pozzolanic activity test cube strengths and the 7-day kiln dust-fly ash-sand control mix cylinder strengths.

In order to determine relationships between various kiln dust properties and kiln dust-fly ash strength, the strength data from the pozzolanic activity tests and the kiln dust-fly ash-sand control mix tests were evaluated by means of linear multiple regression. A stepwise regression program (BMDO2R) was utilized to determine correlations between key physical and chemical parameters of the kiln dust samples and Task B strength data, using both linear and stepwise multiple regression analyses performed separately on the cement kiln dust and lime kiln dust test data.

6.6.1 Analysis of Cube Strengths vs. Kiln Dust Characteristics

All of the kiln dust pozzolanic activity strength values for cube specimens showed a very high correlation coefficient (R) when related to both the free lime content and the Blaine fineness or particle size of the cement kiln dusts. For example, the 7-day accelerated cube strength had a correlation coefficient of .9127 with free lime, .9221 with free lime and Blaine fineness, and .9273 with free lime and particle size (difference between 200 mesh and .02 mm sieve). The best fitting curve (R = .9273) is described by the equation:

$y = 71.38 + 61.75\ X_1 + 2.93\ X_2$ where

y = 7-day accelerated cube strength

X_1 = free lime in kiln dust

X_2 = % passing #200 sieve - % passing .02 mm.

The 28-day ambient cube strength also exhibited good correlation with the same three parameters, although the correlations were not as strong as with the accelerated cure specimens. For example, the 28-day ambient cube strength had a correlation coefficient of .8111 with free lime and .8556 with free lime and particle size. The regression curve for the higher correlation coefficient is:

$y = -51.13 + 34.27\ X + 3.51\ X$ where

y = 28 day ambient cube strength

X_1 = free lime in kiln dust

X_2 = % passing #200 sieve - % passing .02 mm.

Since these equations are considered "best fit" equations and have a correlation coefficient (R) ranging from .8 up to in excess of .9, these equations are considered an accurate way of correlating kiln dust properties with pozzolanic activity test strength data obtained from a blend of kiln dust and a specific fly ash.

6.6.2 Analysis of Carver Cylinder Strengths

Similar regression analyses were performed on the strength values from the Carver size test cylinders containing either kiln dust-fly ash or kiln dust-fly ash-sand aggregate. Only the cement kiln dust data was evaluated because of the anomalies caused by lime kiln dust reactivity. From the simple regression analysis, the strongest direct correlations are kiln dust strength after molding with loss on ignition (R = .5343) and kiln dust strength after 7 days with percent passing the 325 mesh sieve (R = .5317). The highest correlation coefficient (R = .7105) was found when the 7-day compressive strength was related to the Al_2O_3, MgO, and LOI of the fly ash. Since all values were less than the desired minimum correlation of 0.80, no strong correlation was established between kiln dust properties and Carver press strength data.

7. STRENGTH DEVELOPMENT OF KILN DUST-FLY ASH-AGGREGATE MIXTURES

7.1 Purpose of Tests

Selected kiln dust-fly ash mix combinations analyzed during the Task B strength testing were further evaluated for strength development with the addition of different aggregate materials during the Task C phase of the program. The results of the Task C test program served as a screening for selection of a typical range of kiln dust and fly ash samples for evaluation of engineering properties during the final task.

7.2 Selection of Materials for Testing

As shown in Figure 3, the number of kiln dust and fly ash samples tested during the Task C investigation was reduced from the earlier phases of the project. A total of 28 of the 45 kiln dust samples were selected, together with 11 of the 18 fly ash samples. All six of the aggregate sources were included in the Task C testing.

Kiln dust samples were selected for Task C testing on the basis of:

- Geographical distribution
- Range of compressive strength (low, medium, and high)
- Inclusion of cement and lime dusts, principally cement dusts, together with some stockpiled dust samples.

A total of 24 fresh kiln dust samples were chosen for Task C testing. These dusts were combined with a total of 11 fly ash samples. In addition, four dust samples were selected from plant locations which had previously provided a stockpiled dust sample. The strength development of stockpiled dust samples was also determined.

Of the 24 kiln dust samples included in Task C, 6 are lime kiln dusts and 18 are cement kiln dusts. All but two of the kiln dusts are from coal-fired operations; the others are from gas-fired kilns. Of the 11 fly ash samples, three are Class C fly ashes (2 from subbituminous coal and 1 from lignite coal). The remaining 8 fly ash samples are Class F fly ashes, including one sample from the burning of a western bituminous coal.

7.3 Selection of Task C Mixes

All of the kiln dust-fly ash combinations selected for testing were blended with at least two aggregates (limestone and siliceous). Certain kiln dust-fly ash combinations were also blended with either blast furnace slag or granitic gneiss (or both), based on availability of these aggregates within the geographical area of that kiln dust and/or fly ash. The stockpiled dust samples were molded with the same fly ash as corresponding fresh dust samples and combined with the aggregate type that resulted in maximum compressive strength at the optimum kiln dust-fly ash ratio.

To provide an adequate basis for comparison of strength development, a series of control or reference mixes were also prepared. In addition to the kiln dust-fly ash-aggregate test mixes, the following control mixes were also tested:

1. Six control mixes consisting of 4.8 percent high calcium lime, 19.2 percent fly ash FA-16, and 76 percent by weight of aggregate for six sources of aggregate.
2. Six control mixes consisting of 3.6 percent high calcium lime, 14.4 percent fly ash FA-16, and 82 percent by weight of aggregate for the six sources of aggregate.
3. Twenty-four reference mixes consisting of each of the kiln dust samples in the Task C test program, blended with fly ash FA-16 and 76 percent by weight of aggregate B (granitic gneiss). Test specimens for each of these control mixes were prepared at kiln dust-fly ash ratios of 2:1 and 1:1 for cement kiln dust and 1:1 and 1:2 for lime kiln dusts.

7.4 Preparation of Task C Mixes

All Task C test specimens were prepared using Proctor size cylinders, measuring 101.6 mm (4 inches) in diameter by 116.8 mm (4.6 inches) in height. Test specimens were molded and compacted in three layers at or near optimum moisture content in accordance with the procedures described in ASTM C953. Aggregates were screened prior to placing into the mixer and molding. The aggregate fraction retained on the 19.1 mm (3/4 inch) sieve was removed and substituted in the mix with an equivalent fraction of the aggregate minus 19.1 mm (3/4 inch) and plus No. 4 mesh sieve in size.

A series of Proctor tests were performed on randomly selected kiln dust-fly ash-aggregate mix compositions in order to determine target mix densities with which to compare molded mix densities. These mixes served as a means of relating the density at molding with the maximum dry density of typical mix combinations to assure that all test mixes were being prepared at or close to the maximum density.

A comparison was made of the molded densities of Proctor specimens using different aggregate types at different kiln dust-fly ash ratios. There were 8 Task C mix combinations investigated with a total of 31 different moisture-density tests performed. The molded mix densities ranged from 94 to 105 percent of the corresponding maximum Proctor densities with an average of 99.3 percent of Proctor density. From this data, it is reasonable to conclude that the Task C mix test specimens were molded to a density that corresponds very closely to the maximum dry density as determined from Proctor testing.

7.5 Compressive Strength Testing of Task C Mixes

All test specimens prepared during the Task C phase of the program were broken in compressive strength. Throughout most of the testing program, six Proctor size test specimens were prepared for every mix combinations. Three were cured for 7 days at 23°C. (73°F.) and three were cured for 7 days at 38°C. (100°F.). During the latter stages of Task C, only specimens cured at 38°C. (100°F.) were prepared and tested.

The majority of the test mixes evaluated the effect of two different percentages of aggregate in each mix combination. These were 76 and 82 percent by dry weight of total mix. As the testing progressed, it became evident that the development of maximum compressive strengths for the various test mixes was approximately equally divided between these two aggregate percentages. It was concluded that the percentage of aggregate in a given kiln dust-fly ash-aggregate mix was not in most cases significant enough to warrant evaluating two aggregate percentages throughout the entire testing program. Therefore, during the latter portion of the Task C test program, only mixes containing 76 percent aggregate were molded and tested.

A total of 36 control mixes were tested in Task C, including 12 conventional lime-fly ash-aggregate controls and 24 kiln dust-fly ash-aggregate reference mixes. The lime-fly ash-aggregate control mixes were used to compare the strength development of kiln dust-fly ash combinations to corresponding lime-fly ash strengths for the same aggregate. The results of the lime-fly ash-aggregate control mix tests are presented in Table 19. Figure 10 shows a comparison of the strengths of these control mixes. This comparison related the strengths obtained using each of the six aggregates with the minimum 400 psi strength criterion from ASTM C593. As shown in Figure 10, only three of the six lime-fly ash-aggregate control mixes were able to exceed the 400 psi minimum strength.

The kiln dust-fly ash-aggregate reference mixes were used to evaluate the effect on strength development of mixes containing each of the kiln dust samples in the Task C program while holding the source and percentage of the fly ash and the aggregate constant. All kiln dust-fly ash-aggregate reference mixes were made with fly ash FA-16 and 76 percent by weight of Aggregate B (granitic gneiss). The results of the Task C kiln dust-fly ash-aggregate reference mix strength tests are presented in Table 20. Figure 11 shows a comparison of the strengths of reference mixes containing cement kiln dusts. Figure 12 shows a comparison of the strengths of reference mixes containing lime kiln dusts. Figure 13 relates strength development to class of cement kiln dust for these reference mixes. As shown in Figures 11 and 12, all but one of the cement dust mixes and one of the lime dust mixes was able to exceed the 400 psi minimum strength. Figure 13 shows that the higher 7-day mix strengths were attained with Class I and Class III cement dusts, which are the total dusts.

A total of 64 kiln dust-fly ash-aggregate mix combinations were tested in Task C. Using the kiln dust-fly ash strength test data from Task B as a guide, at least two, and in most cases three, kiln dust-fly ash ratios were investigated for each mix combination in Task C. Table 21 lists all the kiln dust-fly ash-aggregate mix combinations in the Task C testing program and presents the maximum strength and optimum kiln dust-fly ash ratio for each of these test mixes. The moisture content and molded density of each of the maximum strength test mixes is also presented. Figure 14 relates the strength development of the Task C test mixes to the fly ash

Table 19

RESULTS OF LIME-FLY ASH AGGREGATE CONTROL MIX STRENGTH TESTS

Control Mix No.	Type of Aggregate	(Mix Composition (Percent by Weight)			Moisture Content (percent)	Density of Mix (pcf)	7-Day Compressive Strength* (psi)
		Lime	Fly Ash	Aggregate			
A	Dolomitic Limestone	4.8	19.2	76	8.4	136.8	768
		3.6	14.4	82	6.8	138.6	781
B	Granitic Gneiss	4.8	19.2	76	7.4	132.1	696
		3.6	14.4	82	7.0	134.5	635
C	Blast Furnace Slag	4.8	19.2	76	6.9	122.5	1154
		3.6	14.4	82	6.8	123.8	1026
D	Sand and Gravel	4.8	19.2	76	6.7	126.8	362
		3.6	14.4	82	6.5	131.5	367
E	Calcitic Limestone	4.8	19.2	76	10.1	118.6	351
		3.6	14.4	82	9.8	119.6	198
F	River Sand	4.8	19.2	76	7.5	126.4	232
		3.6	14.4	82	7.5	127.4	194

*Average of 3 specimens cured for 7 days at 38°C. (100°F.)
1 lb./in.^{2} = .0703 kg/cm^2 1 lb./ft.^{3} = 16.02 kg/m^3

FIGURE 10

COMPRESSIVE STRENGTH OF TASK C
LIME - FLY ASH-AGGREGATE CONTOL MIXES

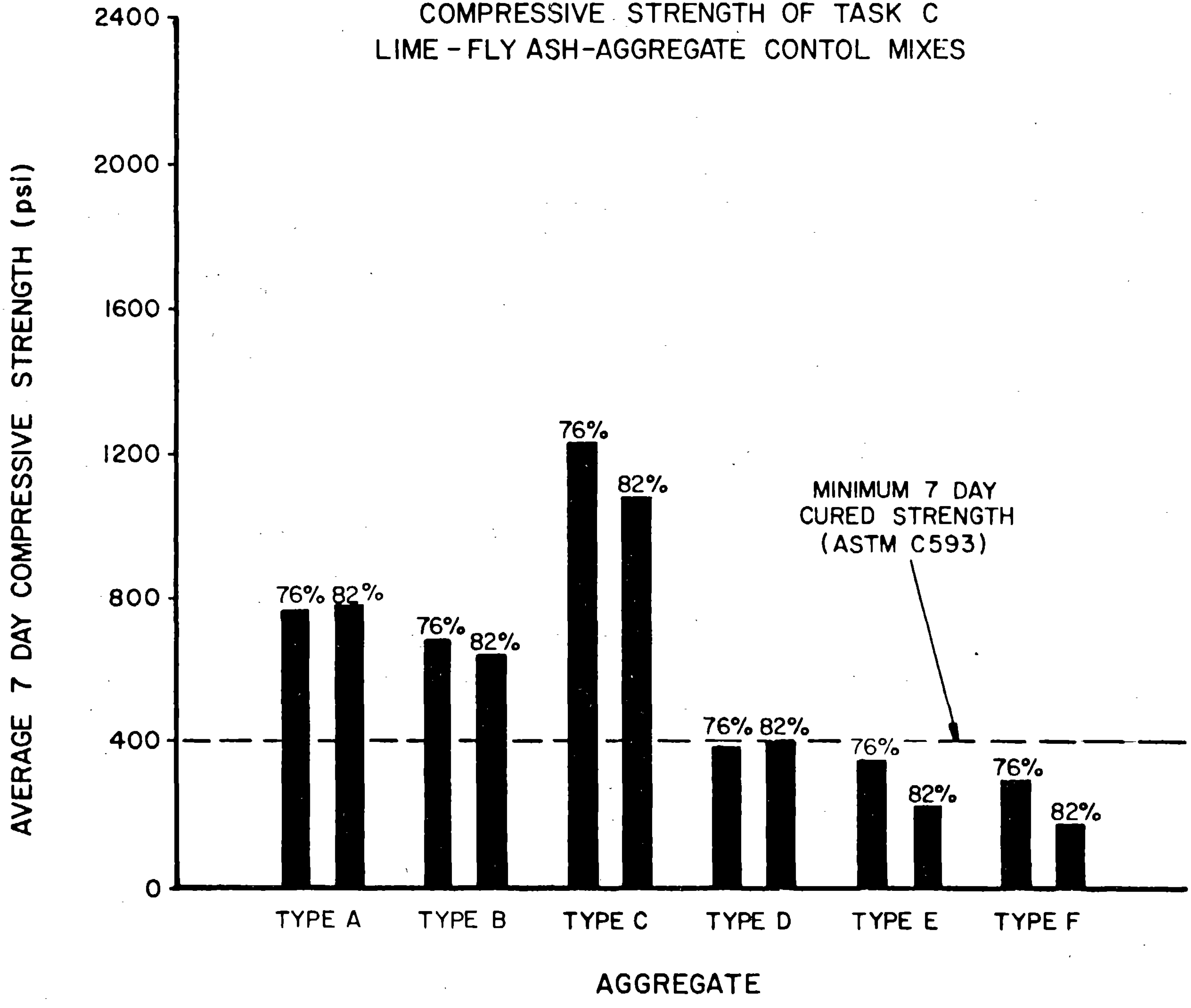


Table 20

RESULTS OF KILN DUST-FLY ASH-AGGREGATE REFERENCE MIX STRENGTH TESTS

Kiln Dust Number	Optimum KD-FA Ratio	Moisture Content (percent)	Density of Mix (PCF)	Maximum Strength* (psi)	Ratio of Task C Control Mix Strength**
CD-1	2:1	10.1	128.1	734 (13)	1.05
CD-3	2:1	9.9	128.8	1213 (8)	1.74
CD-4	2:1	9.5	130.0	581 (15)	0.83
CD-6	2:1	8.1	133.6	562 (16)	0.81
CD-8	2:1	9.0	137.1	1301 (5)	1.87
CD-10	2:1	8.7	130.9	1159 (9)	1.67
CD-12	2:1	9.7	131.3	477 (17)	0.69
CD-13	1:1	8.5	131.6	1441 (4)	1.95
CD-14	2:1	9.1	131.9	719 (14)	1.03
CD-15	2:1	9.3	131.1	115 (18)	0.17
CD-16	2:1	8.7	131.5	845 (11)	1.21
CD-17	2:1	9.4	129.1	801 (12)	1.15
CD-18	2:1	8.7	131.0	989 (10)	1.42
CD-19	1:1	9.1	128.6	1948 (2)	2.80
CD-20	2:1	7.8	133.0	1282 (6)	1.84
CD-28	2:1	10.2	127.6	2001 (1)	2.88
CD-29	2:1	9.7	128.4	1444 (3)	2.07
CD-30	2:1	9.2	130.3	1281 (7)	1.84
LD-1	1:1	10.3	126.3	973 (2)	1.40
LD-2	1:1	9.6	129.6	606 (4)	0.87
LD-3	1:1	8.3	131.6	1669 (1)	2.40
LD-4	1:1	10.2	127.9	888 (3)	1.28
LD-7	1:2	10.0	126.8	191 (6)	0.27
LD-11	1:1	8.3	131.8	564 (5)	0.81

*Average of 3 specimens cured for 7 days at 38°C. (100°F.)

**Compared with maximum 7-day strength of lime-fly ash-aggregate control mix using Aggregate B.

1 lb./in.^{2} = .0703 kg/cm^2 1 lb./ft.^{3} = 16.02 kg/m^3

FIGURE 11

COMPRESSIVE STRENGTH OF TASK C
CEMENT KILN DUST-FLY ASH-AGGREGATE CONTROL MIXES

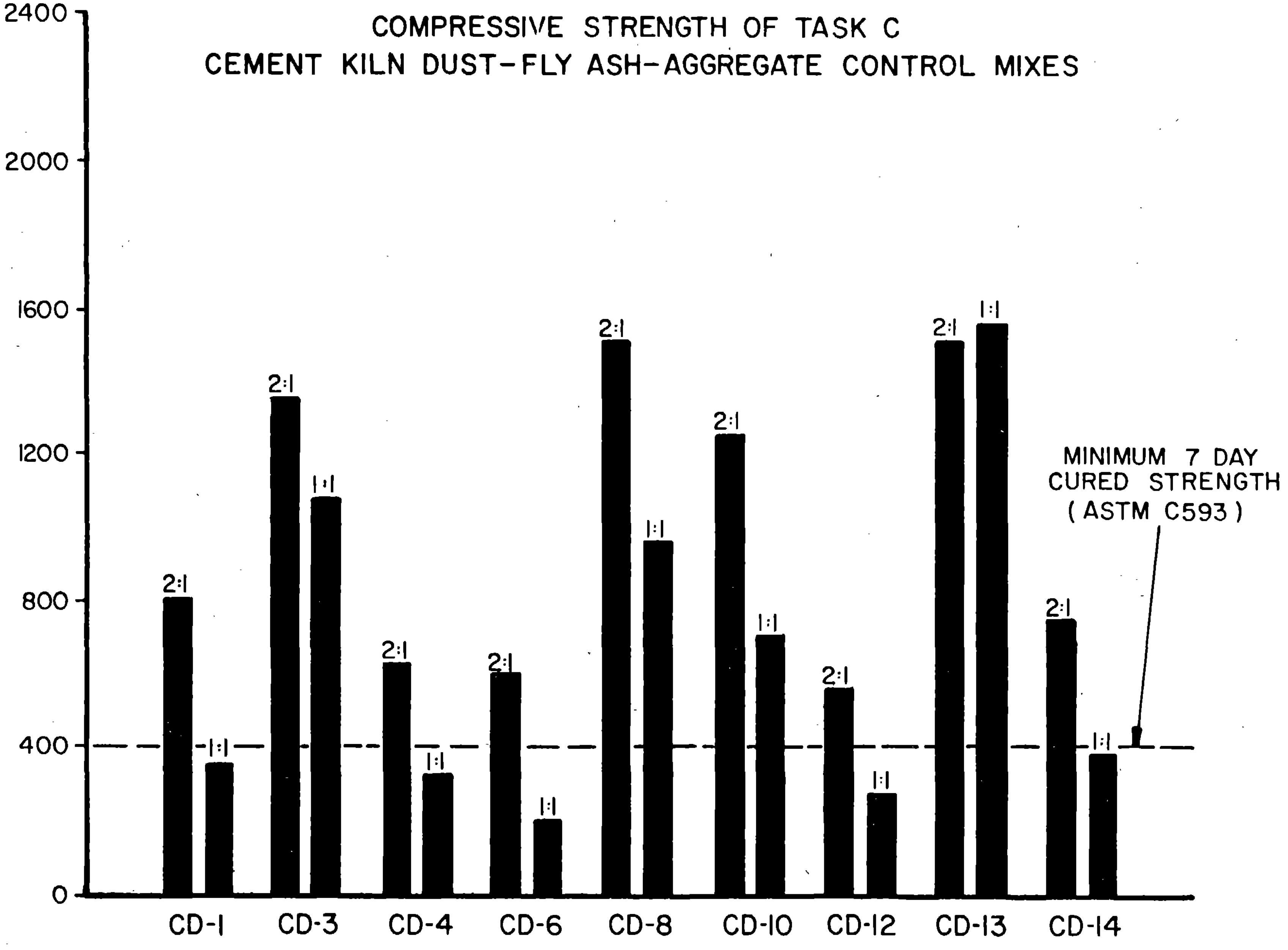
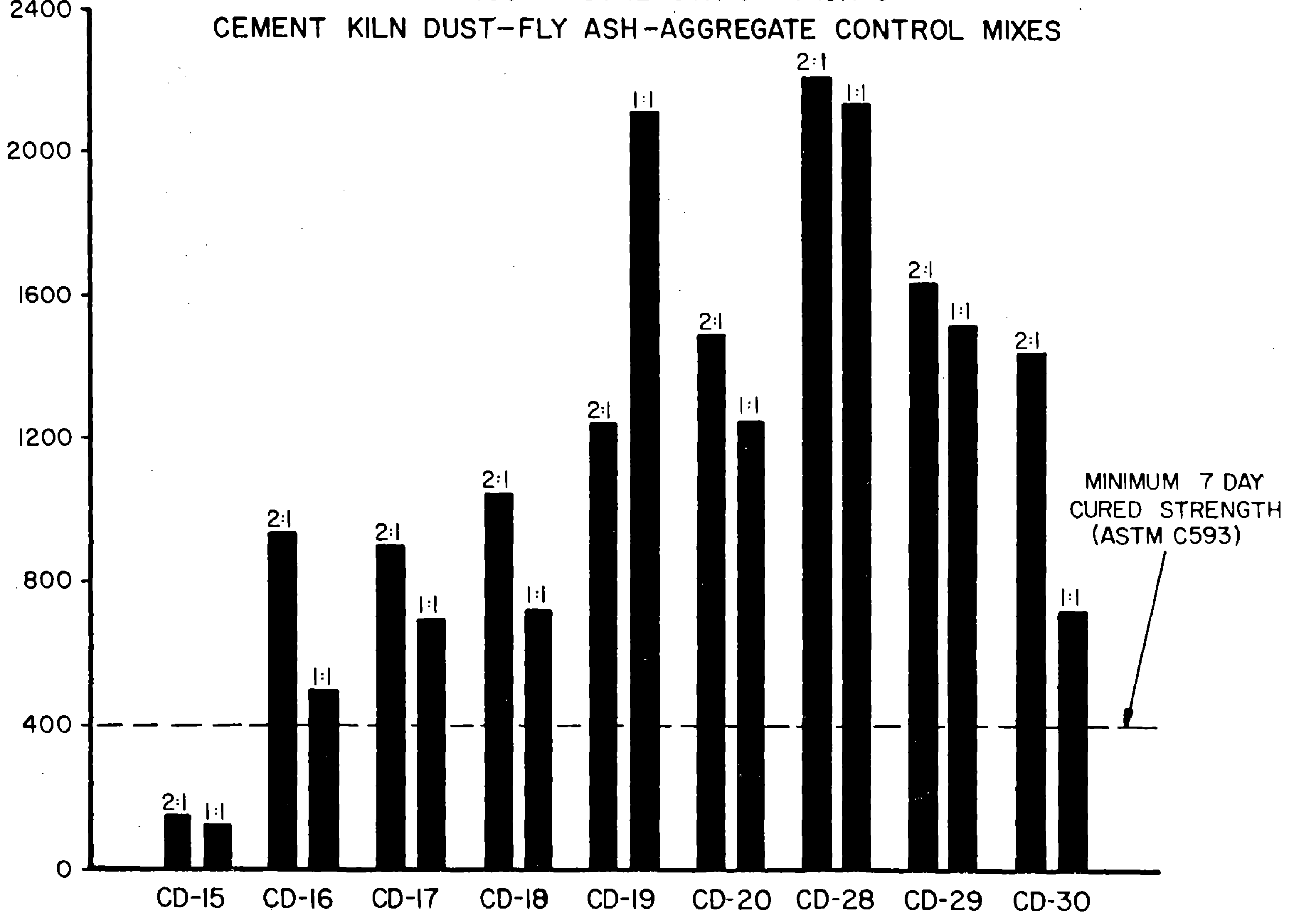


FIGURE 11 (continued)



COMPRESSIVE STRENGTH OF TASK C
CEMENT KILN DUST-FLY ASH-AGGREGATE CONTROL MIXES

FIGURE 12

COMPRESSIVE STRENGTH OF TASK C
LIME KILN DUST-FLY ASH-AGGREGATE CONTROL MIXES

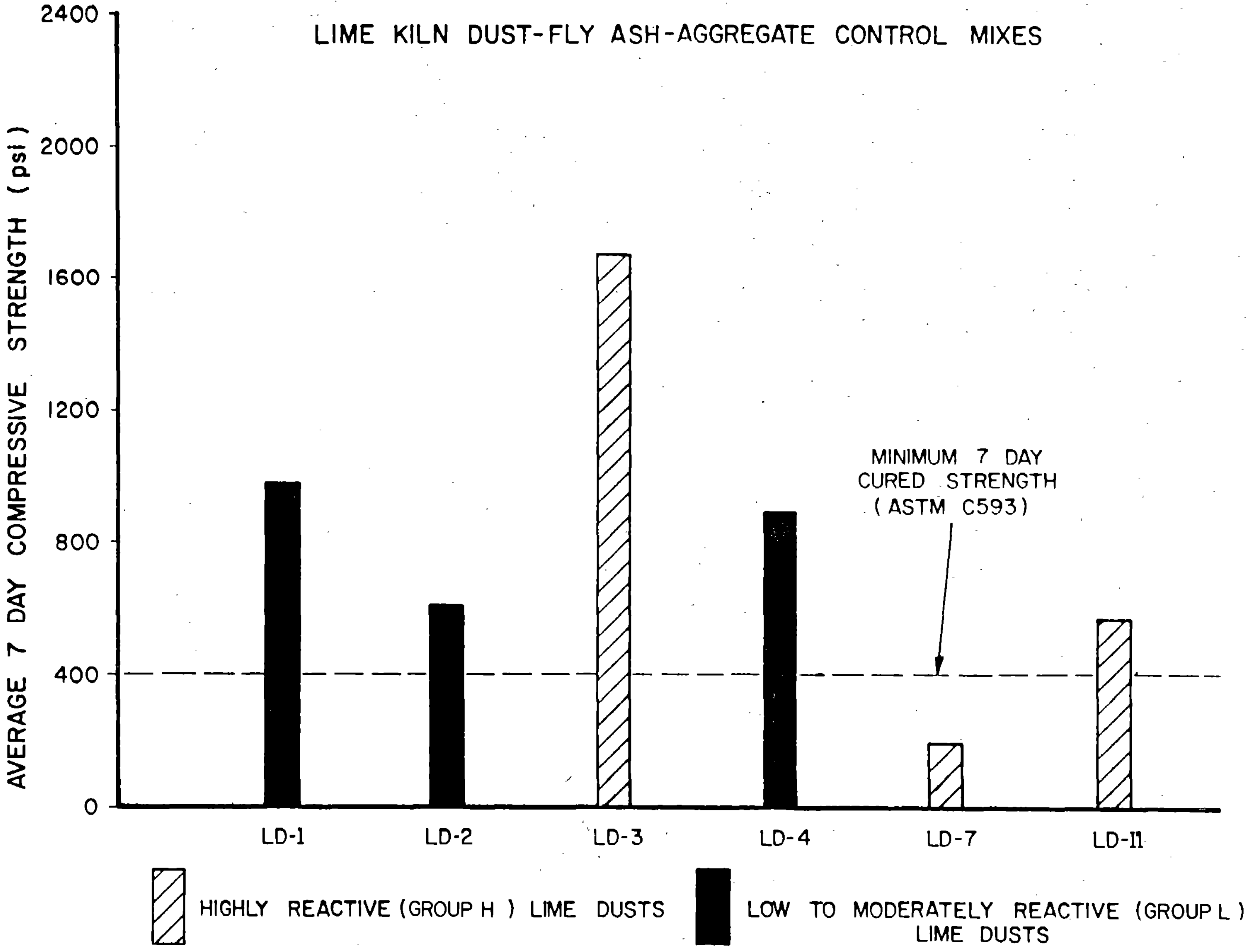


FIGURE 13

KILN DUST CLASS vs. COMPRESSIVE STRENGTH OF TASK C

KILN DUST-FLY ASH-AGGREGATE CONTROL

OR REFERENCE MIXES

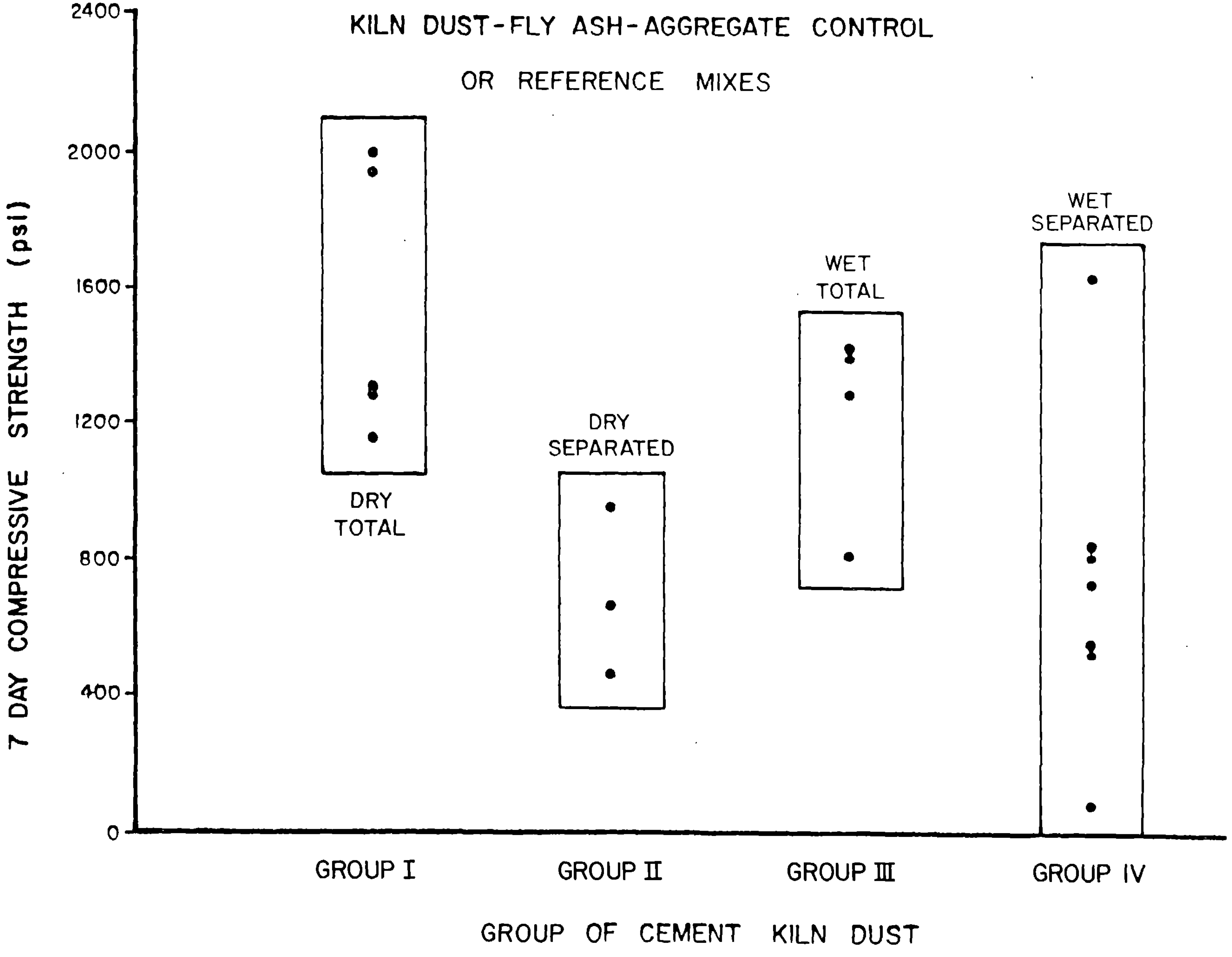


Table 21

RESULTS OF KILN DUST-FLY ASH-AGGREGATE TASK C MIX STRENGTH TESTS

Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Optimum Aggregate Percentage	Optimum KD-FA Ratio	Moisture Content (Percent)	Density of Mix (PCF)	Maximum Strength* (psi)
2	CD-3	FA-14	A	82	1:1	5.3	141.9	1012
			D	82	1:1	7.6	136.6	1177
5	LD-1	FA-7	A	82	1:2	6.0	144.0	1204
			D	76	1:1	7.4	134.7	1122
6	CD-6	FA-7	A	76	1.5:1	5.4	146.9	1276
			B	82	1.5:1	6.7	135.6	968
			C	76	1.5:1	7.4	131.7	1274
			D	76	2:1	9.2	134.5	760
9	CD-1	FA-5	A	82	2:1	7.0	132.9	1142
			D	76	2:1	7.0	132.1	1058
10	LD-4	FA-5	A	76	1:1	6.6	141.2	2639
			D	82	2:1	6.9	140.1	1567
12	LD-3	FA-2	A	76	1:2	6.2	149.2	2123
			B	76	2:1	9.4	130.7	1159
			C	76	1:2	9.5	134.0	1773
			D	76	1:2	7.7	137.5	1934
13	CD-18	FA-2	A	76	1:2	5.9	146.2	3103
			D	82	1:2	6.0	143.8	2056
14	CD-20	FA-2	A	76	2:1	6.1	146.3	2338
			D	76	1:2	7.3	138.9	1762
17	CD-8	FA-11	C	76	1:1	7.2	133.5	2570
			E	76	1:1	8.0	127.7	1264
			F	82	1:1	7.9	135.3	1491

Table 21 (contd.)

RESULTS OF KILN DUST-FLY ASH-AGGREGATE TASK C MIX STRENGTH TESTS

Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Optimum Aggregate Percentage	Optimum KD-FA Ratio	Moisture Content (Percent)	Density of Mix (PCF)	Maximum Strength* (psi)
18	LD-7	FA-11	E	82	1:1	8.5	126.7	818
			F	76	1:1	5.9	135.2	771
19	CD-17	FA-11	A	76	1.5:1	7.3	142.8	1421
			D	76	1.5:1	7.9	133.3	1126
			E	76	1:1	6.8	125.2	934
			F	82	1:1	5.2	136.5	1198
27	CD-30	FA-4	E	76	1:1	8.0	127.3	976
			F	82	2:1	6.0	138.0	1580
28	LD-11	FA-4	E	82	1:2	8.0	126.1	505
			F	82	1:1	6.0	135.6	365**
30	CD-28	FA-4	E	76	1:1	8.0	122.5	1319
			F	76	2:1	6.0	133.7	2199
33	CD-13	FA-15	A	76	1:1	6.7	140.4	1548
			D	76	2:1	7.6	133.8	858
37	CD-12	FA-9	A	76	2:1	6.1	144.7	1423
			C	76	2:1	9.0	132.9	1298
			D	82	3:1	6.2	142.9	991
42	CD-29	FA-17	E	76	1:1	8.0	124.0	589
			F	76	1:2	6.0	133.0	552
49	CD-15	FA-3	A	76	3:1	7.3	142.8	248**
			D	76	1:1	7.4	137.3	95**
51	CD-10	FA-3	A	76	2:1	6.9	137.4	1733
			B	76	2:1	10.1	129.3	979
			C	76	2:1	9.4	125.3	951
			D	76	2:1	9.0	131.7	1126

Table 21 (contd.)

RESULTS OF KILN DUST-FLY ASH-AGGREGATE TASK C MIX STRENGTH TESTS

Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Optimum Aggregate Percentage	Optimum KD-FA Ratio	Moisture Content (Percent)	Density of Mix (PCF)	Maximum Strength* (psi)
61	LD-2	FA-16	A	76	1:1	10.7	133.1	988
			B	76	1:1	7.7	133.2	679
			C	76	1:1	7.7	130.2	1186
			D	76	2:1	9.0	130.3	914
62	CD-14	FA-16	A	76	2:1	7.5	139.3	1252
			B	76	1.5:1	8.8	132.4	680
			C	76	2:1	9.4	131.3	1107
			D	76	1.5:1	7.0	134.7	670
63	CD-16	FA-16	A	76	2:1	8.4	137.1	1346
			D	76	2:1	10.2	128.9	842
64	CD-19	FA-16	A	76	1:2	9.1	133.5	2811
			D	76	1:2	8.7	129.7	1993
65	CD-4	FA-7	A	76	2:1	6.7	143.4	1413
			B	76	2:1	7.5	133.9	568
			C	76	1:1	7.0	131.1	1286
			D	76	2:1	7.8	132.3	734
			MIXES CONTAINING STOCKPILED KILN DUST					
30-S	CD-26	FA-4	E	76	1:1	N.A.	N.A.	624
61-S	LD-8	FA-16	B	76	1:2	N.A.	N.A.	65**
64-S	CD-23	FA-16	B	76	1:1	N.A.	N.A.	54**
65-S	CD-31	FA-7	B	76	2:1	N.A.	N.A.	438

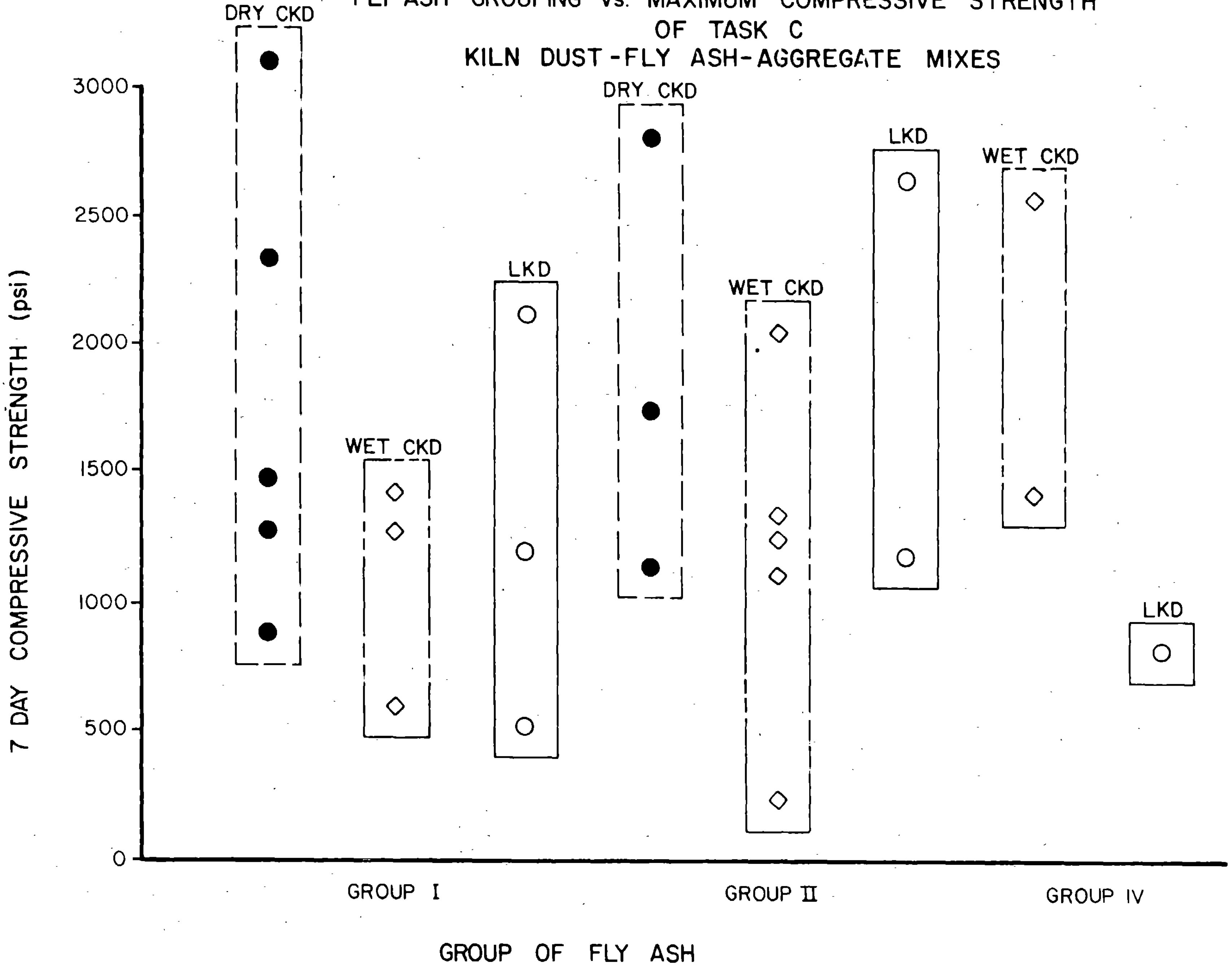
*Average of 3 specimens cured for 7 days at 38°C. (100°F.)
**Lower 7 day strength than ASTM C593 400 psi minimum. N.A. denotes information not available.

1 lb./in.^{2} = .0703 kg/cm.^{2} 1 lb./ft.^{3} = 1602 kg/cm.^{3}

FIGURE 14

FLY ASH GROUPING vs. MAXIMUM COMPRESSIVE STRENGTH OF TASK C

KILN DUST-FLY ASH-AGGREGATE MIXES



grouping and class of kiln dust. Figure 14 shows that, regardless of the class of fly ash used, highest strengths were generally obtained with dry cement dusts.

Table 22 compares the maximum strengths of the kiln dust-fly ash-aggregate test mixes with the strength of lime-fly ash-aggregate control mixes containing the same aggregate. Of the 64 mix combinations tested, 57 of the kiln dust-fly ash-aggregate mixes (or 89.1 percent) exceeded the strength of lime-fly ash-aggregate control mixes with the same aggregate. In 34 of these 54 mixes, the kiln dust-fly ash-aggregate compressive strengths were more than double that of the lime-fly ash-aggregate control mix strengths. Only one of the kiln dusts tested (CD-15) was unable to exceed lime-fly ash-aggregate control mix strengths with any aggregate. However, it should be noted that kiln dust concentrations in the test mixes were considerably higher than concentrations of commercial hydrated lime in the control mixes.

The data in Table 22 clearly indicate that an overwhelming majority of kiln dust-fly ash-aggregate mixes are able to develop 7-day compressive strengths equal to or well in excess of the strengths obtained from comparable lime-fly ash-aggregate compositions. This data provides definite evidence that, from the standpoint of early strength development, kiln dusts can be considered suitable replacements for hydrated lime in lime-fly ash-aggregate pavements systems, when used in higher concentrations with fly ash than normally used for lime.

Table 23 presents a comparison of the maximum compressive strength of kiln dust-fly ash-aggregate test mixes with the compressive strength of kiln dust-fly ash-aggregate reference mixes. In essence, the data in Table 22 is a measure of the effect using different fly ashes and aggregates in the test mixes exerts on strength development compared to the control fly ash (FA-16). Only 19 of 64 mix combinations (29.7 percent) showed a decrease in strength when a fly ash other than the control fly ash was used. The most significant increases in strength over the control mixes were noted with the use of Class C fly ashes (FA-2, FA-9, and FA-11). For the 20 mix combinations in which a Class C fly ash was used, the average increase in strength over similar mixes using the control fly ash was 92 percent. This is an indication that higher levels of early strength development can be anticipated when Class C fly ashes are used in pozzolanic base mixes.

7.6 Correlation of Task C Strength Data with Characterization Results

Linear and multiple regression techniques were also used to define relationships between the compressive strength development of Task C kiln dust-fly ash-aggregate control mixes and the physical and chemical characteristics of the cement kiln dusts used in these mixes. The same stepwise regression program (BMDO2R) that was used to analyze the Task B test data was also used to analyze the Task C control mix data. The 7-day compressive strengths of the kiln dust-fly ash-aggregate control mixes containing cement kiln dust were used as the dependent variable, while twelve physical or chemical properties of the 18 cement kiln dusts used in the Task C testing were the independent variables. Correlation coefficients were determined for each of the independent variables separately and in combination with each other.

Table 22

COMPARISON OF OPTIMUM KILN DUST-FLY ASH-AGGREGATE MIX STRENGTHS VS. LIME-FLY ASH-AGGREGATE CONTROL MIX STRENGTHS

				Lime-Fly Ash-Aggregate Control Mix Data		Kiln Dust-Fly Ash-Aggregate Task C Mix Data			Ratio of Task C Control Strength
Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Percent Aggregate	Compressive Strength*	Percent Aggregate	KD-FA Ratio	Compressive Strength*	
2	CD-3	FA-14	A	82	781	82	1:1	1012	1.30
			D	82	367	82	1:1	1177	3.21
5	LD-1	FA-7	A	82	781	82	1:2	1204	1.54
			D	82	367	76	1:1	1122	3.06
6	CD-6	FA-7	A	82	781	76	1.5:1	1276	1.63
			B	76	696	82	1.5:1	968	1.39
			C	76	1154	76	1.5:1	1274	1.10
			D	82	367	76	1:2	760	2.07
9	CD-1	FA-5	A	82	781	82	2:1	1142	1.46
			D	82	367	76	2:1	1058	2.88
10	LD-4	FA-5	A	82	781	76	1:1	2639	3.38
			D	82	367	82	2:1	1567	4.27
12	LD-3	FA-2	A	82	781	76	1:2	2123	2.72
			B	76	696	76	2:1	1159	1.67
			C	76	1154	76	1:2	1934	1.68
			D	82	367	76	1:2	1773	4.83
13	CD-18	FA-2	A	82	781	76	1:2	3102	3.97
			D	82	367	82	1:2	2056	5.60
14	CD-20	FA-2	A	82	781	76	2:1	2338	2.99
			D	82	367	76	1:2	1762	4.80
17	CD-8	FA-11	C	76	1154	76	1:1	2570	2.22
			E	76	351	76	1:1	1264	3.60
			F	76	232	76	1:1	1491	6.43

Table 22 (contd.)

COMPARISON OF OPTIMUM KILN DUST-FLY ASH-AGGREGATE MIX STRENGTHS VS. LIME-FLY ASH-AGGREGATE CONTROL MIX STRENGTHS

Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Lime-Fly Ash-Aggregate Control Mix Data		Kiln Dust-Fly Ash-Aggregate Task C Mix Data			Ratio of Task C Control Strength
				Percent Aggregate	Compressive Strength*	Percent Aggregate	KD-FA Ratio	Compressive Strength*	
18	LD-7	FA-11	E	76	351	82	1:1	818	2.33
			F	76	232	76	1:1	771	3.32
19	CD-17	FA-11	A	82	781	76	1.5:1	1421	1.82
			D	82	367	76	1:1	1126	3.07
			E	76	351	76	1:1	934	2.66
			F	76	232	76	1:1	1086	4.68
27	CD-30	FA-4	E	76	351	76	1:1	976	2.78
			F	76	232	82	2:1	1580	6.81
28	LD-11	FA-4	E	76	351	82	1:2	505	1.44
			F	76	232	82	1:1	365	1.57
30	CD-28	FA-4	E	76	351	76	1:1	1319	3.76
			F	76	232	76	2:1	2199	9.48
33	CD-13	FA-15	A	82	781	76	1:1	1548	1.98
			D	82	367	76	2:1	858	2.34
37	CD-12	FA-9	A	82	781	76	2:1	1423	1.82
			C	76	1154	76	2:1	1298	1.12
			D	82	367	82	3:1	991	2.70
42	CD-29	FA-17	E	76	351	76	1:1	589	1.68
			F	76	232	76	1:2	552	2.38
49	CD-15	FA-3	A	82	781	76	3:1	248	0.32
			D	82	367	76	1:1	95	0.26

Table 22 (contd.)

COMPARISON OF OPTIMUM KILN DUST-FLY ASH-AGGREGATE MIX STRENGTHS VS. LIME-FLY ASH-AGGREGATE CONTROL MIX STRENGTHS

				Lime-Fly Ash-Aggregate Control Mix Data		Kiln Dust-Fly Ash-Aggregate Task C Mix Data			Ratio of Task C Control Strength
Mix No.	Kiln Dust Number	Fly Ash Number	Aggregate Type	Percent Aggregate	Compressive Strength*	Percent Aggregate	KD-FA Ratio	Compressive Strength*	
51	CD-10	FA-3	A	82	781	76	2:1	1733	2.22
			B	76	696	76	2:1	979	1.41
			C	76	1154	76	2:1	951	0.82
			D	82	367	76	2:1	1126	3.07
61	LD-2	FA-16	A	82	781	76	1:1	988	1.27
			B	76	696	76	1:1	679	0.98
			C	76	1154	76	1:1	1186	1.03
			D	82	367	76	2:1	914	2.49
62	CD-14	FA-16	A	82	781	76	2:1	1252	1.60
			B	76	696	76	1.5:1	680	0.98
			C	76	1154	76	2:1	1107	0.96
			D	82	367	76	1.5:1	670	1.83
63	CD-16	FA-16	A	82	781	76	2:1	1346	1.72
			D	82	367	76	2:1	842	2.29
64	CD-19	FA-16	A	82	781	76	1:2	2811	3.60
			D	82	367	76	1:2	1993	5.43
65	CD-4	FA-7	A	82	781	76	2:1	1413	1.81
			B	76	696	76	2:1	568	0.82
			C	76	1154	76	1.5:1	1286	1.11
			D	82	367	76	2:1	734	2.00

Strength values given in psi   1 lb/in.^{2} = .0703 kg/cm^2

* Strength values represent average of three test specimens at each kiln dust cured for 7 days at 38^{o}C. (100^{o}F.)

Table 23

COMPARISON OF OPTIMUM KILN DUST-FLY ASH-AGGREGATE MIX STRENGTHS VS. KILN DUST-FLY ASH-AGGREGATE REFERENCE MIX STRENGTHS

		Kiln Dust-Fly Ash-Aggregate Reference Mix Data*			Kiln Dust-Fly Ash-Aggregate Task C Mix Data				
Mix No.	Kiln Dust Number	Optimum KD-FA Ratio	Compressive Strength (psi)	Fly Ash Number	Aggregate Type	Percent Aggregate	Optimum KD-FA Ratio	Compressive Strength (psi)	Ratio of Task C to Control Strength
2	CD-3	2:1	1213	FA-14	A	82	1:1	1012	0.83
					D	82	1:1	1177	0.97
5	LD-1	2:1	973	FA-7	A	82	1:2	1204	1.24
					D	82	1:1	1122	1.15
6	CD-6	2:1	562	FA-7	A	76	1.5:1	1276	2.27
					B	82	1.5:1	968	1.72
					C	76	1.5:1	1274	2.27
					D	76	1:2	760	1.35
9	CD-1	2:1	734	FA-5	A	82	2:1	1142	1.56
					D	76	2:1	1058	1.44
10	LD-4	2:1	888	FA-5	A	76	1:1	2639	2.97
					D	82	2:1	1567	1.76
12	LD-3	1:1	1669	FA-2	A	76	1:2	2123	1.27
					B	76	2:1	1159	0.69
					C	76	1:2	1934	1.16
					D	76	1:2	1773	1.06
13	CD-18	2:1	989	FA-2	A	76	1:2	3102	3.14
					D	82	1:2	2056	2.08
14	CD-20	2:1	1282	FA-2	A	76	2:1	2338	1.82
					D	76	1:2	1762	1.37

Table 23 (Continued)

		Kiln Dust-Fly Ash-Aggregate Reference Mix Data*			Kiln Dust-Fly Ash-Aggregate Task C Mix Data				
Mix No.	Kiln Dust Number	Optimum KD-FA Ratio	Compressive Strength (psi)	Fly Ash Number	Aggregate Type	Percent Aggregate	Optimum KD-FA Ratio	Compressive Strength (psi)	Ratio of Task C to Control Strength
17	CD-8	2:1	1301	FA-11	C	76	1:1	2570	1.98
					E	76	1:1	1264	0.97
					F	82	1:1	1491	1.15
18	LD-7	1:2	191	FA-11	E	82	1:1	818	4.28
					F	76	1:1	771	4.04
19	CD-17	2:1	801	FA-11	A	76	1.5:1	1421	1.77
					D	76	1.5:1	1126	1.41
					E	76	1:1	934	1.17
					F	76	1:1	1086	1.36
27	CD-30	2:1	1281	FA-4	E	76	1:1	976	0.76
					F	82	2:1	1580	1.23
28	LD-11	1:1	564	FA-4	E	82	1:2	505	0.90
					F	82	1:1	365	0.65
30	CD-28	2:1	2001	FA-4	E	76	1:1	624	0.31
					F	76	1:2	886	0.44
33	CD-13	2:1	1441	FA-15	A	76	1:1	1548	1.07
					D	76	2:1	858	0.60
37	CD-12	2:1	477	FA-9	A	76	2:1	1423	2.98
					C	76	2:1	1298	2.72
					D	82	3:1	991	2.08
42	CD-29	2:1	1444	FA-17	E	76	1:1	589	0.41
					F	76	1:2	552	0.38

Table 23 (Continued)

COMPARISON OF OPTIMUM KILN DUST-FLY ASH-AGGREGATE MIX STRENGTHS
VS. KILN DUST-FLY ASH-AGGREGATE REFERENCE MIX STRENGTHS

		Kiln Dust-Fly Ash-Aggregate Reference Mix Data*			Kiln Dust-Fly Ash-Aggregate Task C Mix Data				
Mix No.	Kiln Dust Number	Optimum KD-FA Ratio	Compressive Strength (psi)	Fly Ash Number	Aggregate Type	Percent Aggregate	Optimum KD-FA Ratio	Compressive Strength (psi)	Ratio of Task C to Control Strength
49	CD-15	2:1	115	FA-3	A	76	3:1	248	2.16
					D	76	1:1	95	0.83
51	CD-10	2:1	1159	FA-3	A	76	2:1	1733	1.50
					B	76	2:1	979	0.84
					C	76	2:1	951	0.82
					D	76	2:1	1126	0.97
61	LD-2	1:1	606	FA-16	A	76	1:1	988	1.63
					B	76	1:1	679	1.12
					C	76	1:1	1186	1.96
					D	76	2:1	914	1.51
62	CD-14	2:1	719	FA-16	A	76	2:1	1252	1.74
					B	76	1.5:1	680	0.95
					C	76	2:1	1107	1.54
					D	76	1.5:1	670	0.93
63	CD-16	2:1	845	FA-16	A	76	2:1	1346	1.59
					D	76	2:1	842	1.00
64	CD-19	1:1	1948	FA-16	A	76	1:2	2811	1.44
					D	76	1:2	1993	1.02
65	CD-4	2:1	581	FA-7	A	76	2:1	1413	2.43
					B	76	2:1	568	0.98
					C	76	1.5:1	1286	2.21
					D	76	2:1	734	1.26

*Reference mix for each kiln dust contains FA-16 and 76 percent by weight Aggregate B (granitic gneiss).

NOTE: 1 lb./in.^{2} = .0703 kg/cm^2

The cement kiln dust parameters that correlated most closely with the 7-day compressive strengths of the Task C control mixes were the free lime, total calcium oxide, Blaine fineness, and particle size distribution. Various combinations of these parameters showed high correlation coefficients (R). The best fitting curve (R = .910) is described by the equation:

$y = 325.26 + 46.42\ X_1 + 22.23\ X_2 - 0.06\ X_3 + 2.02\ X_4$ where

y = 7 day kiln dust-fly ash-aggregate control mix strength

X_1 = free lime in kiln dust

X_2 = total CaO content of kiln dust

X_3 = Blaine fineness of kiln dust

X_4 = % passing #200 sieve - % passing .02 mm.

The next best fitting curve (R = .904) is described the the equation:

$y = 549.36 + 51.97\ X_1 + 19.99\ X_2 - 0.07\ X_3$ where

y = 7 day kiln dust-fly ash-aggregate control mix strength

X_1 = free lime in kiln dust

X_2 = total CaO content of kiln dust

X_3 = Blaine fineness of kiln dust.

Each of these equations has a correlation coefficient (R) in excess of .9 and is considered an accurate way of correlating the 7-day compressive strength of kiln dust-fly ash-aggregate mixes with key parameters of cement kiln dust. These equations are valid for mixes using a single source of fly ash and a single source of aggregate. When the source of the fly ash and the source of the aggregate are varied, these equations cannot be applied.

In addition to regression analysis, an attempt was also made to correlate the compressive strength of kiln dust-fly ash-aggregate test specimens with the chemical constituents theoretically available for reacting with fly ash in a pozzolanic system. These constituents basically include the following:

- Oxide, silicate, or aluminate compounds of calcium and magnesium (possibly including residual cement content)
- Alkali compounds in the form of sodium and potassium oxides.

The reactive compounds of calcium and magnesium in a kiln dust can be determined in an approximate fashion by deducting the loss on ignition (LOI), which is mostly carbon in the form of calcium or magnesium carbonate, from the total calcium oxide and magnesium oxide values given in the chemical analysis. The alkalis, comprised of sodium and potassium oxides, should also be included, although beyond a certain alkali level, the presence of the alkalis may no longer be helpful, and could possibly even be harmful. A discussion in the recent patent literature (33) indicates that an alkali level of 6 percent may be considered an upper limit in terms of beneficial alkali chemistry in pozzolanic or cementitious reactions. Since sulfate is essentially a retarder, the presence of sulfates in relatively large amounts (10 percent or greater) probably inhibit the pozzolanic and/or cementitious reactions which would normally develop between the alkaline and alkali constituents in kiln dust and fly ash.

To determine the total reactive oxides (alkalines plus alkalis) in a given sample of kiln dust, the following formula is suggested:

$$\text{Total Reactive Oxides} = [(CaO + MgO) - LOI] + (K_2O + Na_2O)$$

where the suggested maximum allowable value of the alkalis ($K_2O + Na_2O$) for use in the equation is 6 percent. Although the numerical value of the total reactive oxides for a given sample of kiln dust may not in itself be highly significant, it should provide a reasonable guideline for evaluating the potential reactivity of a given fly ash source.

The total reactive oxides were determined for each of the cement and lime kiln dust samples included in the Task C kiln dust-fly ash-aggregate control mix cylinders. Table 24 shows the ranking of these 24 kiln dusts according to Task C control mix strength and also shows the various chemical constituents and the resultant value of the total reactive oxides for each dust sample. As shown in this table, as the compressive strength declines, the value of the total reactive oxide for each dust also diminishes, except for certain Class A lime kiln dusts. Figure 15 graphically shows the relationship between the total reactive oxides and the Task C control mix strength development. With the cement kiln dusts, it can be seen in Figure 15 that the control mix strength is directly related to the total reactive oxides in the kiln dust. With the lime kiln dusts, the relationship is not as direct because of the presence of high levels of free lime in the Class A lime dusts, which must be conditioned prior to mixing.

Table 24

COMPARISON OF KILN DUST-FLY ASH-AGGREGATE REFERENCE MIX STRENGTHS VS. TOTAL REACTIVE OXIDES OF KILN DUSTS

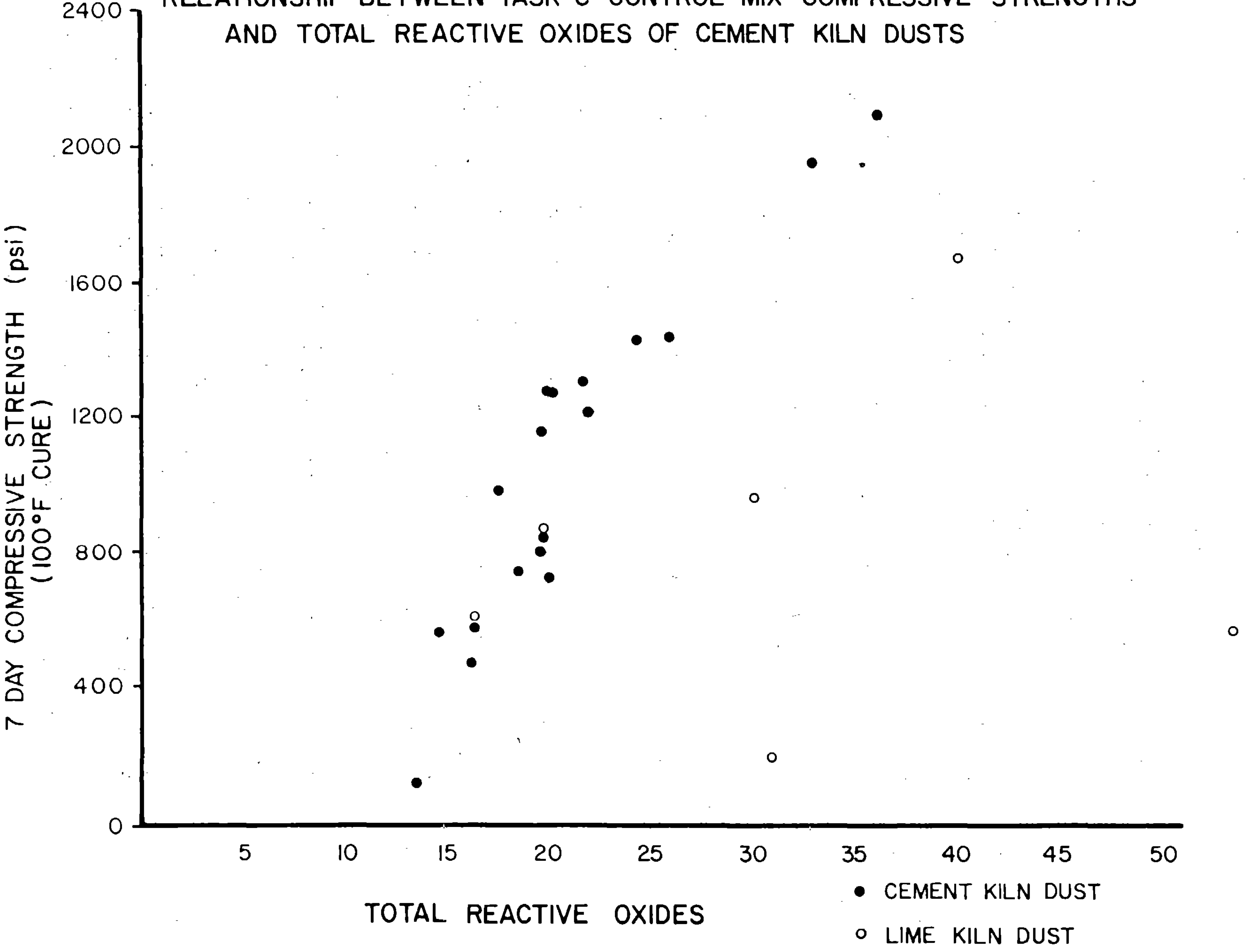
	Cement Dust Number	Optimum KD-FA Ratio	Maximum 7-Day Strength	Group of Dust	CaO	MgO	LOI	Net Reactive Alkaline	Alkalis	Total Reactive Oxide
1.	CD-28	2:1	2001	I	49.7	1.73	18.7	32.7	4.43	37.2
2.	CD-19	1:1	1948	I	41.1	1.30	11.7	30.7	3.59	34.3
3.	CD-29	2:1	1444	III	47.5	1.20	24.1	24.6	2.32	26.9
4.	CD-13	1:1	1441	III	45.2	1.37	23.2	23.4	1.96	25.4
5.	CD-8	2:1	1301	III	39.4	0.92	22.7	17.6	5.10	22.7
6.	CD-20	2:1	1282	I	45.5	1.16	28.4	18.3	2.78	21.1
7.	CD-30	2:1	1281	I	43.0	3.28	27.1	19.2	2.37	21.6
8.	CD-3	2:1	1213	IV	39.1	2.63	22.8	18.9	4.07	23.0
9.	CD-10	2:1	1159	I	45.9	1.39	28.2	19.1	1.61	20.7
10.	CD-18	2:1	989	II	47.6	1.33	31.6	17.3	1.19	18.5
11.	CD-16	2:1	845	IV	37.4	1.96	24.0	15.4	5.51	20.9
12.	CD-17	2:1	801	III	26.8	0.54	13.5	13.8	13.87	19.8
13.	CD-1	2:1	734	II	38.3	2.49	25.3	15.5	4.21	19.7
14.	CD-14	2:1	719	IV	34.6	1.83	22.9	13.5	7.63	19.5
15.	CD-4	2:1	581	IV	37.2	2.02	27.3	11.9	5.38	17.3
16.	CD-6	2:1	562	IV	25.8	1.13	19.5	7.4	16.65	13.4
17.	CD-12	2:1	477	II	44.4	1.66	31.8	14.3	2.94	17.2
18.	CD-15	2:1	115	IV	19.4	0.64	13.2	6.8	15.44	12.8

	Lime Dust Number	Optimum KD-FA Ratio	Maximum 7-Day Strength	Group of Dust	CaO	MgO	LOI	Net Reactive Alkaline	Alkalis	Total Reactive Oxide
1.	LD-3	1:1	1669	H	54.5	0.49	14.2	40.8	0.25	41.1
2.	LD-1	1:1	973	L	28.5	20.5	18.2	30.8	0.70	31.5
3.	LD-4	1:1	888	L	44.3	3.56	27.5	20.4	0.52	20.8
4.	LD-2	1:1	606	L	31.2	23.5	37.4	17.3	0.09	17.4
5.	LD-11	1:1	564	H	62.4	0.70	8.47	54.6	0.28	54.9
6.	LD-7	1:2	191	H	58.0	0.43	27.6	30.8	0.10	30.9

NOTE: Strength values given in psi. $1 \text{ lb./in.}^2 = .0703 \text{ kg/cm.}^2$

FIGURE 15

RELATIONSHIP BETWEEN TASK C CONTROL MIX COMPRESSIVE STRENGTHS AND TOTAL REACTIVE OXIDES OF CEMENT KILN DUSTS



8. OTHER ENGINEERING PROPERTIES OF KILN DUST-FLY ASH-AGGREGATE MIXTURES

8.1 Purpose of Tests

The first three work tasks focused on: kiln dust and fly ash characteristics; kiln dust-fly ash strength development relationships; and the comparative strength characteristics of a spectrum of kiln dust-fly ash-aggregate material combinations. Although the results of these tests do considerably expand the amount of currently available data in these areas, there is a notable lack of information available regarding the engineering properties of kiln dust-fly ash-aggregate mixtures. Some data on the field performance of kiln dust-fly ash-aggregate compositions is available from literature related to demonstration projects.(36, 37) However, there is very little in the way of laboratory test data with respect to such properties as durability, volume stability, and long-term strength development for kiln dust-fly ash-aggregate compositions.

The work performed in Task D was aimed at providing needed laboratory test data pertaining to the engineering properties of selected kiln dust-fly ash-aggregate mix combinations from Task C.

8.2 Selection of Test Mixes

Mix combinations selected for Task D were based on the following criteria:

- Geographic distribution.
- Range of maximum strength values (low, medium, and high).
- Emphasis on cement kiln dusts, but with at least one high calcium and one dolomitic lime kiln dust.
- Inclusion of at least one Class C fly ash.
- Inclusion of two limestone and two siliceous aggregates.
- Matching a high alkali cement kiln dust with an aggregate having potential for alkali-aggregate reactivity.

A total of four control mixes and ten kiln dust-fly ash-aggregate combinations were evaluated in Task D. Each of the four control mixes consisted of 4.8 percent calcitic hydrated lime, 19.2 percent fly ash FA-16, and 76 percent aggregate. Control mixes were prepared for two limestone aggregates (A and E) and two siliceous aggregates (D and F). The ten kiln dust-fly ash-aggregate mixes in Task D involved four dolomitic limestone mixes, one mix with siliceous sand and gravel, three calcite limestone mixes, and two mixes with river sand. These ten mixes were selected in order to evaluate a representative cross-section of kiln dust-fly ash-aggregate combinations believed typical of those which may be considered for future field demonstration projects.

8.3 Description of Test Methods

A total of 30 Proctor size cylinders were molded and tested for each of the Task D control and kiln dust-fly ash-aggregate mixes. These cylinders were prepared in accordance with ASTM C593 at the respective optimum moisture contents determined in Task C. The materials for each Task D mix combination were blended in proportions corresponding to the maximum strength mix determined in Task C. Each of the 30 cylinder specimens for a particular mix was numbered consecutively in the order in which the specimens were prepared. At the conclusion of specimen preparation, random numbers were used to group specimens for determination of the following engineering properties:

- Long-term compressive strength (15 cylinders)

  38°C. (100°F.) curing - 3 specimens each tested at 14 and 28 days
  23°C. (73°F.) curing - 3 specimens each tested at 28, 60, and 90 days.

  The results of the 14 and 28 day accelerated cure strength tests were also compared with the 7 day accelerated cure strengths determined from the durability testing phase described below.

- Freeze-thaw durability (6 cylinders)

  All specimens cured at 100°F. for 7 days, then:
  Two specimens soaked for 4 hours, capped and tested for strength in accordance with ASTM C593 procedures.
  Two capped specimens tested for compressive strength after vacuum saturation in accordance with ASTM C593 procedures.
  Two specimens tested for weight loss and volume change after freezing and thawing, in accordance with ASTM D560 procedures.

- Dimensional stability (3 cylinders)

  Specimens cured at 73°F. in sealed cans placed in 100 percent relative humidity moist room.
  Specimens measured weekly for height and diameter changes at top and bottom quarter points to determine volumetric expansion or contraction over a 56-day period.

- Autogenous healing (5 cylinders)

  Specimens cured under pre-determined conditions, tested for compressive strength, allowed to continue curing under the same conditions, and retested for compressive strength following the continuation of curing.

  All specimens were inspected during the continuation of curing in order to monitor healing of cracks from initial compressive strength testing. Observations were made concerning the extent to which specimen cracks were recemented during the healing period and whether or not the specimens failed along previous crack patterns as a result of retesting.

The following curing conditions were adopted:

Curing Temperature	Initial Curing Period	Continued Curing Period*	Ultimate Curing Period
38°C. (100°F.)	7 days	7 days	14 days
38°C. (100°F.)	14 days	14 days	28 days
23°C. (73°F.)	7 days	21 days	28 days
23°C. (73°F.)	14 days	46 days	60 days
23°C. (73°F.)	28 days	62 days	90 days

*Considered as time available for autogenous healing.

- Resilient modulus (1 cylinder)

  One specimen from each test mix was cured at 73°F. in a sealed can for a minimum time period of 28 days.

  The test specimen was then placed in a diametral testing machine and tested to determine the resilient modulus (repeated loading), and the splitting tensile strength, in accordance with ASTM D3497.

8.4 Discussion of Task D Test Results

8.4.1 Long-Term Compressive Strength

Table 25 presents the results of the long-term strength tests performed on the four control mixes and ten kiln dust-fly ash-aggregate test mixes. The data in this table clearly show that most kiln dust-fly ash-aggregate mixes develop significant gains in strength with time, similar to or in some cases greater than that exhibited by lime-fly ash-aggregate mixes. Eight of the ten kiln dust-fly ash-aggregate test mixes exhibited higher compressive strength after 28 days of ambient cure than lime-fly ash-aggregate control mixes containing the same source of aggregate.

The majority of the kiln dust-fly ash-aggregate test mixes had 28 day ambient cure strengths that were at least 75 percent of the corresponding 28-day accelerated cure strength, whereas the 28-day ambient cure strengths of the lime-fly ash-aggregate mixes were only 30 to 50 percent of the corresponding 28-day accelerated cure strengths. For mixes containing Class C fly ash, rapid early strength development was observed, as expected, followed by relatively small increases in strength over extended periods of time. This pattern appears to be consistent regardless of whether ambient or accelerated curing conditions were involved.

The 7 and 28-day accelerated cure strength data presented in Table 25 are comparable to data reported from a recent laboratory study of the behavior of kiln dust-fly ash-aggregate compositions utilizing both Class C and Class F fly ashes.(38) One of the significant findings from this study was that the 7 and 28-day accelerated strengths of mixes containing Class C fly ash varied inversely with the length of time that elapsed between mixing

Table 25

RESULTS OF LONG-TERM COMPRESSIVE STRENGTH TESTING OF TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	Kiln Dust-Fly Ash Ratio	LONG-TERM COMPRESSIVE STRENGTH (psi)					
					ACCELERATED CURE			AMBIENT CURE		
					7 days	14 days	28 days	28 days	60 days	90 days
Control A	Lime	FA-16	A	1:4	879	1980	2393	1212	2135	2395
Control D	Lime	FA-16	D	1:4	199	522	1295	377	812	1193
Control E	Lime	FA-16	E	1:4	621	1119	1430	403	847	1090
Control F	Lime	FA-16	F	1:4	659	1556	1925	407	957	1372
6-A	CD-6	FA-7	A	1:1	917	1051	1318	1116	1321	1298
6-F	CD-6	FA-7	F	2:1	388	517	628	626	834	819
10-A	LD-4	FA-5	A	1:1	1846	2599	2665	2043	3050	3156
10-D	LD-4	FA-5	D	1:1	1441	1945	2067	1504	1816	1973
13-A	CD-18	FA-2*	A	1:2	2078	2253	2279	1623	2291	2410
19-F	CD-17	FA-11*	F	1:1	1588	1762	1944	1713	2233	2245
28-E	LD-11	FA-4	E	1:2	696	1554	1908	442	1177	1991
42-E	CD-29	FA-17	E	1:1	633	1044	1114	943	N.A.	1501
61-A	LD-2	FA-16	A	1:1	1311	1592	1841	1478	1741	2101
62-A	CD-14	FA-16	A	1.5:1	929	1006	1161	1022	1169	1228

NOTE: Strength values are average of 3 specimens. 1 lb./in.^{2} = .0703 kg/cm.^{2}

N.A. denotes information not available.

*Indicates Class C fly ash.

and compaction, i.e., the longer the storage time, the lower the short-term and long-term strength development. In addition, 28 day strengths were found to not be significantly higher than 7 day strengths under accelerated curing conditions, which essentially confirms the findings of this study. No decrease in strength relative to time between mixing and compaction was noted in mixes using Class F fly ash.(38)

It was concluded from the above referenced data that, for lime or kiln dust-fly ash-aggregate mixes containing Class C fly ash, it is important that such mixes be placed and compacted as quickly as possible in order to achieve maximum strength. For similar mixes in which Class F fly ash is used, no similar precautions appear to be needed.

From Table 25, it is evident that significant strength development occurs over extended time periods with most kiln dust-fly ash-aggregate mixes. As shown in Table 22, most kiln dust-fly ash-aggregate mixes also exhibit relatively high early strength gains when compared to conventional lime-fly ash-aggregate mixes.

8.4.2 Durability

The durability of fourteen Task D mixes was evaluated by means of the freeze-thaw test procedures for soil-cement described in ASTM D560.(39) This test involves alternate freezing and thawing cycles with wire brushing of the vertical surface of the test sample following each thaw cycle. A total freeze-thaw cycle comprises 48 hours. The test involves a total of 12 cycles with a maximum allowable loss in weight of 10 percent. This test does not necessarily reflect actual field conditions.

The results of the freeze-thaw tests are summarized in Table 26. The weight loss for each of the four control mix samples was quite low, ranging from 0.6 to 5.9 percent. Of the ten kiln dust-fly ash-aggregate mixes tested in Task D, only three were unable to pass the freeze-thaw test. Two were mixes containing CD-6, both of which had extremely high weight loss values, (16.2 and 54.5 percent). The third was a mix containing CD-14, which had a 12-cycle weight loss of 13.8 percent. The remaining seven kiln dust-fly ash-aggregate mixes exhibited excellent resistance to freezing and thawing, with weight losses that ranged from 0.2 to 2.2 percent.

One mix which failed the freeze-thaw test with a 13.8 percent weight loss, contained CD-14, which had a relatively high sulfate content (8.6 percent) and a total reactive oxide value which is comparatively low (19.5), as shown in Table 24. Although this mix had an unacceptable 12 cycle weight loss, it showed only a 1.45 percent weight loss after 6 freeze-thaw cycles.

The two mixes which failed the freeze-thaw test with extremely high weight loss values each contained CD-6, which has an exceptionally high sulfate content (17.4 percent). This is an indication that high levels of sulfate in kiln dusts can be a deterrent to strength development and durability. However, mix D19-F, which had a very low freeze-thaw weight loss (2.2 percent), contained CD-17, which also has a high sulfate content (12.4 percent). Although CD-17 has a higher amount of total reactive oxides than CD-6 (18.8 to 12.4), the principal difference between the mixes containing CD-6 and the mix

Table 26

RESULTS OF FREEZE-THAW TESTING OF TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	Kiln Dust-Fly Ash Ratio	FREEZE-THAW TEST RESULTS		
					Final Volume*	Wt. Loss 6 Cycles	Wt. Loss 12 Cycles
Control A	Lime	FA-16	A	1:4	99.01	0.33	1.18
Control D	Lime	FA-16	D	1:4	101.42	0.67	5.87
Control E	Lime	FA-16	E	1:4	100.03	0.17	1.75
Control F	Lime	FA-16	F	1:4	100.20	0.04	0.64
6-A	CD-6	FA-7	A	1:1	104.73	1.59	16.20**
6-F	CD-6	FA-7	F	2:1	104.85	7.56	54.47**
10-A	LD-4	FA-5	A	1:1	100.00	0.08	0.20
10-D	LD-4	FA-5	D	1:1	100.46	0.13	0.21
13-A	CD-18	FA-2	A	1:2	99.74	0.28	1.07
19-F	CD-17	FA-11	F	1:1	98.90	1.00	2.19
28-E	LD-11	FA-4	E	1:2	100.23	0.66	1.08
42-E	CD-29	FA-17	E	1:1	99.60	0.10	0.75
61-A	LD-2	FA-16	A	1:1	100.74	0.54	1.19
62-A	CD-14	FA-16	A	1.5:1	100.62	1.45	13.79**

*Expressed as percent of original volume from computations of diameter and height changes.
**Considered failing in freeze-thaw. Weight loss values expressed as a percent.

containing CD-17 is that the mix containing CD-17 was combined with a Class C fly ash, which resulted in significantly higher early compressive strength. Therefore, it may be possible to utilize marginal kiln dusts if a Class C fly ash is used.

Both of the kiln dust-fly ash-aggregate mixes containing Class C fly ash exhibited excellent freeze-thaw durability, even the mix in which the Class C fly ash was combined with a high sulfate cement kiln dust. From the limited data available, it appears that the high initial strength gain characteristics of Class C fly ash are able to create a sufficiently strong matrix to offset the potentially disruptive reactions that can sometimes occur between the calcium, sulfates, and aluminates when using high sulfate kiln dusts.

With the exception of the two high sulfate kiln dusts which were unable to pass the freeze-thaw test, the use of kiln dust with fly ash and aggregate results in extremely durable, stable compositions. Some combinations of kiln dust and fly ash do provide high 7-day strengths under ambient as well as accelerated curing conditions. Such early strength development and high resistance to freezing and thawing are factors that may justify considering possible extension of normal cut-off dates for late season construction.

Durability was also evaluated by means of the vacuum saturation test procedure described in ASTM C593. This procedure was developed as a rapid means of correlating with the strength of a specimen exposed to ten cycles of freezing and thawing under temperature conditions and freeze-thaw cycle lengths similar to those actually experienced within a pavement system in the field (40). In order to pass this test, a minimum compressive strength of 400 psi must be attained after curing for 7 days and testing under vacuum saturation.

Table 27 compares the vacuum saturation strength values with the 7 day compressive strength values reported in Table 25. In general, the two strength values were comparable for most mixes. The data in Table 27 indicates that only one control and one kiln dust-fly ash-aggregate mix were unable to pass the vacuum saturation test. However, two other mixes containing kiln dust failed the freeze-thaw test, but developed acceptable vacuum saturation strength.

8.4.3 Dimensional Stability

A possible concern related to the use of kiln dust-fly ash-aggregate mixes in highway construction is the dimensional stability of such mixes. Normally, the hydration of free lime is accompanied by chemical changes which release heat energy and result in expansive reactions that can sometimes be detrimental to a pavement. Such activity often occurs in the presence of excess water. In addition, the formation of ettringite and in some cases brucite are known to be expansive reactions which can cause distress in concrete if not developed early and if present above tolerable levels(41).

A series of dimensional measurements were made on kiln dust-fly ash-

Table 27

COMPARISON OF VACUUM SATURATION STRENGTH VS. 7 DAY COMPRESSIVE STRENGTH AND FREEZE-THAW TEST RESULTS FOR TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	7 Day Compressive Strength (psi)	Vacuum Saturation Strength (psi)	12 Cycle Freeze-Thaw Weight Loss (percent)
Control A	Lime	FA-16	A	879	790	1.18
Control D	Lime	FA-16	D	199	201	5.87
Control E	Lime	FA-16	E	621	N.A.	1.75
Control F	Lime	FA-16	F	659	717	0.64
6-A	CD-6	FA-7	A	917	939	16.20
6-F	CD-6	FA-7	F	388	N.A.	54.47
10-A	LD-4	FA-5	A	1846	1792	0.20
10-D	LD-4	FA-5	D	1441	1557	0.21
13-A	CD-18	FA-2	A	2078	1623	1.07
19-F	CD-17	FA-11	F	1588	1633	2.19
28-E	LD-11	FA-4	E	696	810	1.08
42-E	CD-29	FA-17	E	633	662	0.75
61-A	LD-2	FA-16	A	1311	N.A.	1.19
62-A	CD-14	FA-16	A	929	828	13.79

N.A. denotes information not available.
1 lb./in.^{2} = .0703 kg/cm^2

aggregate test specimens and lime-fly ash-aggregate control mix specimens over different time periods. Measurements for dimensional stability were taken at designated height and diameter locations on each of the test specimens after 28 and 56 days of either moist room curing or total saturation at ambient temperature. Average height and diameter measurements were used to compute specimen volumes, which were then compared to the initial volumes of each of the respective test specimens.

The results of the volume stability testing are presented in Table 28. These data are expressed in terms of the percentage of original specimen volume after 28 or 56 days of exposure either to moist room or saturated conditions. For practical purposes, a change in volume of 0.5 percent was considered marginally acceptable, while a change in volume of 1.0 percent (which corresponds to a linear variation in diameter and height of approximately 0.5 percent) was considered unacceptable from the standpoint of volume stability.

Using a 1.0 percent volume change (either expansion or contraction) as the maximum tolerable limit, all but three of the kiln dust-fly ash-aggregate test specimens performed acceptably under moist room curing conditions. A number of test specimens, including several lime-fly ash-aggregate control mixes, actually showed a decrease in volume under moist room curing conditions.

When considering the possible use of dolomitic lime kiln dusts, it is important to study the mineralogy of a particular lime dust sample in order to determine if some of the dolomite (MgO) exists in the form of periclase. It has been reported (42) that the hydration of periclase is delayed reaction usually taking years, but accompanied by gradual and eventually substantial increases in volume. The reactivity of the dolomitic lime is temperature related. Dead burned dolomitic lime normally contains coarse-grained periclase which is considered relatively stable. Soft burned dolomitic lime, on the other hand, is porous, fine-grained, and more reactive, so that it is easily hydrated to form brucite or $Mg(OH)_2$ in an expansive reaction. If rapid cooling or quenching is used, periclase will form in an amorphous or glassy state and will not be expansive (43). Therefore, in the case of dolomitic lime dusts, it is important to be aware of kiln operating conditions and to evaluate the mineralogy of such dusts prior to use in order to avoid potentially expansive reactions due to periclase hydration.

8.4.4 Autogenous Healing

The term "autogenous healing" refers to the phenomenon in which cracks in a pavement material, if allowed to remain in a relatively undisturbed condition over an extended period of time, will tend to heal or re-cement themselves together, while at the same time the material is continuing to gain strength. Autogenous healing is a reflection of the ability of a pozzolanic base material to continue to increase in strength despite the appearance of cracks or a temporary interruption in normal strength gain conditions.

Table 29 presents the comparative compressive strength results of the five test specimens for each of the control mixes and lime-fly ash-aggregate

Table 28

RESULTS OF DIMENSIONAL STABILITY TESTING OF TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	Kiln Dust Fly Ash Ratio	Volume as Percent of Original: Cured in Moist Room: After 28 Days	Volume as Percent of Original: Cured in Moist Room: After 56 Days	Volume as Percent of Original: Completely Submerged: After 28 Days	Volume as Percent of Original: Completely Submerged: After 56 Days
Control A	Lime	FA-16	A	1:4	100.11	99.56	99.86	100.02
Control D	Line	FA-16	D	1:4	99.33	99.30	99.79	99.06
Control E	Lime	FA-16	E	1:4	100.79	100.84	100.19	98.09*
Control F	Lime	FA-16	F	1:4	100.97	101.19*	99.64	99.87
6-A	CD-6	FA-7	A	1:1	100.42	101.25*	98.81*	100.19
6-F	CD-6	FA-7	F	2:1	100.19	100.55	100.32	101.01*
10-A	LD-4	FA-5	A	1:1	99.48	99.03	100.13	99.95
10-D	LD-4	FA-5	D	1:1	100.06	100.23	100.39	100.76
13-A	CD-18	FA-2	A	1:2	101.27*	101.66*	100.34	100.62
19-F	CD-17	FA-11	F	1:1	99.73	99.19	100.21	100.13
28-E	LD-11	FA-4	E	1:2	100.84	101.26*	99.66	100.33
42-E	CD-29	FA-17	E	1:1	100.54	100.29	100.01	100.87
61-A	LD-2	FA-16	A	1:1	99.81	100.40	101.00*	101.09*
62-A	CD-14	FA-16	A	1.5:1	99.40	99.59	99.98	100.18

*Considered to be a potentially detrimental change in volume.

NOTE: Volume computed based on measured changes in height and diameter.

Table 29

RESULTS OF COMPRESSIVE STRENGTH PERCENT GAIN FROM AUTOGENOUS HEALING TESTING OF TASK D MIXES

	Strength Gain After Curing at 23°C. (73°F.)						Strength Gain After Curing at 38°C. (100°F.)			
	Specimen 1		Specimen 2		Specimen 3		Specimen 4		Specimen 5	
Mix Number	7 days	28 days	14 days	60 days	28 days	90 days	7 days	14 days	14 days	28 days
Control A	274	943	652	1874	1460	2706	947	1492	2426	3103
Control D	103	298	215	680	374	1110	191	414	565	1130
Control E	95	410	147	704	406	1046	879	1253	1157	1408
Control F	48	258	135	N.A.	416	1321	768	1523	1635	1957
6-A	441	1154	712	1078	1074	1329	994	1185	1006	1185
6-F	338	581	465	879	609	873	461	617	427	644
10-A	453	1607	1492	2247	2053	2406	1917	2319	2665	1675
10-D	463	994	1249	1237	1555	1571	1496	1412	1667	1122
13-A*	565	1587	1122	2100	1798	1949	2108	2080	2426	1929
19-F*	1424	1762	1567	2152	1977	2466	1591	1917	1874	1874
28-E	171	414	231	943	529	1993	1002	1567	1627	2104
42-E	306	800	569	1284	811	1082	686	1146	1050	1185
61-A	306	1225	947	1718	1432	1718	1392	1488	1619	1663
62-A	632	923	827	1082	923	1201	867	1014	1030	915

NOTE: Strength values given in psi. 1 lb./in.^{2} = .0703 kg/cm^2

N.A. denotes information not available.
*Mixes contain Class C fly ash.

test mixes. It can be readily seen from the data shown in this table that it is possible to develop compressive strengths substantially higher than initial test strengths under all of the follow-up curing conditions shown in this table. Significant strength gains after initial testing were observed in control mixes as well as kiln dust-fly ash-aggregate test mixes. Again, it is interesting to note that 28 day ambient cure strengths for 9 of the 10 test mixes are comparable to (or in some cases greater than) 28 day accelerated cure strengths, while the 28 day ambient cure strengths for the four control mixes are only 15 to 30 percent of the 28 day accelerated cure strengths. This is indicative of the more rapid early strength gain potential of most kiln dust-fly ash-aggregate mix combinations, even under ambient curing conditions.

Table 30 presents a summary of the percentage gain in compressive strength for each of the five additional curing periods, which include both ambient as well as accelerated curing temperatures. All of the control mixes tested were able to exceed 100 percent of their original test strength after additional curing for each of the five curing conditions. In some instances, strength gains as high as 400 percent or more of original test strength were noted.

Of the 50 kiln dust-fly ash-aggregate autogenous healing test specimens tested, only 7 were unable to exceed 100 percent of their original test strength after additional curing. In five of these instances, very good or excellent strength values were attained from the initial testing. The remaining two specimens were able to regain from 89 to 99 percent of their original test strength. Strength gains of up to, or even slightly in excess of, 400 percent were also noted in the retesting of the kiln dust-fly ash-aggregate test mixes. The data from Table 30 indicates that kiln dust-fly ash-aggregate mixes continue to gain in strength and recement across old cracks similar to the lime-fly ash-aggregate mixes, although perhaps not to as great an extent as the control mixes.

8.4.5 Resilient Modulus

The fundamental stress-strain characteristics of kiln dust-fly ash-aggregate compositions were determined and compared with those of conventional lime-fly ash-aggregate mixtures. The splitting tensile strength and the dynamic or resilient modulus (M_R) of each of the Task D mixes were obtained by means of a standard test method originally developed for evaluation of asphalt test specimens. The resilient modulus testing was performed on Proctor-size cylindrical specimens ranging from 75 to 125 days in age, using a gyratory testing machine in accordance with procedures described in ASTM D3497 (44).

The results of the resilient modulus tests are summarized in Table 31. This table also presents a comparison of test values for kiln dust-fly ash-aggregate test mixes with test values for lime-fly ash-aggregate control mixes in which the same source of aggregate is used. From Table 31, it can be seen that all but one of the kiln dust-fly ash-aggregate mixes had a higher resilient modulus value than the corresponding lime-fly ash-aggregate

Table 30

SUMMARY OF AUTOGENOUS HEALING TESTING OF TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	Percent of Original Strength After Additional Curing Periods				
				38°C. (100°F.) Cure		23°C. (73°F.) Cure		
				7 days	14 days	21 days	46 days	62 days
Control A	Lime	FA-16	A	158	128	344	287	185
Control D	Lime	FA-16	D	217	200	289	316	297
Control E	Lime	FA-16	E	143	122	432	479	258
Control F	Lime	FA-16	F	198	120	538	N.A.	317
6-A	CD-6	FA-7	A	119	118	262	152	124
6-F	CD-6	FA-7	F	134	151	172	189	143
10-A	LD-4	FA-5	A	121	63	355	151	117
10-D	LD-4	FA-5	D	94	67	216	99	101
13-A	CD-18	FA-2	A	99	79	281	187	109
19-F	CD-17	FA-11	F	120	100	124	137	125
28-E	LD-11	FA-4	E	156	129	242	408	377
42-E	CD-29	FA-17	E	167	113	261	226	133
61-A	LD-2	FA-16	A	107	103	400	181	120
62-A	CD-14	FA-16	A	117	89	146	130	130

NOTE: Percent of original strength after additional curing determined by dividing strength at end of curing by original test strength, as given in Table 29.

N.A. denotes information not available.

Table 31

RESULTS OF RESILIENT MODULUS TESTING OF TASK D MIXES

Mix Number	Kiln Dust	Fly Ash	Aggregate	Age at Test	Resilient Modulus (psi)	Percent of Control	Splitting Tensile Strength (psi)	Percent of Control
Control A	Lime	FA-16	A		1.4×10^6	100.0	277	100.0
Control D	Lime	FA-16	D		3.7×10^5	100.0	205	100.0
Control E	Lime	FA-16	E	81 days	1.3×10^6	100.0	169	100.0
Control F	Lime	FA-16	F	89 days	1.4×10^6	100.0	187	100.0
6-A	CD-6	FA-7	A		1.6×10^6	114.3	205	74.0
6-F	CD-6	FA-7	F	123 days	1.0×10^6	71.4	130	69.5
10-A	LD-4	FA-5	A		2.1×10^6	150.0	329	118.8
10-D	LD-4	FA-5	D	76 days	2.6×10^6	702.7	306	149.3
13-A	CD-18	FA-2*	A	88 days	3.1×10^6	221.4	356	128.5
19-F	CD-17	FA-11*	F	118 days	3.3×10^6	235.7	442	236.4
28-E	LD-11	FA-4	E	115 days	2.0×10^6	153.8	254	150.3
42-E	CD-29	FA-17	E	125 days	1.6×10^6	123.1	190	112.4
61-A	LD-2	FA-16	A	91 days	1.7×10^6	121.4	214	77.3
62-A	CD-14	FA-16	A	73 days	1.8×10^6	128.6	204	73.6

NOTES: 1. The resilient modulus (M_R) of Portland cement concrete normally ranges from 3.5×10^6 psi for 3000 psi concrete to 4×10^6 psi for 5000 psi concrete.

2. 1 lb./in.^{2} = .0703 kg/cm.^{2}

*Class C fly ash.

mix. The one exception was a mix containing CD-6, a high sulfate cement kiln dust. The two test mixes (13-A and 19-F) containing Class C fly ash each had a resilient modulus value comparable to that of Portland cement concrete. Most of the other test mixes had resilient modulus values one-half to two-thirds that of Portland cement concrete.

Three of the ten kiln dust-fly ash-aggregate mixes developed lower splitting tensile strength than comparable lime-fly ash-aggregate mixes. Two of these three mixes contained CD-6, the high sulfate cement kiln dust used in Task C and D mixes which also developed low compressive strengths. The third mix contained a dolomitic limestone dust. In most instances, the splitting tensile strength is approximately 15 percent of the compressive strength.

9. CONCLUSIONS

These conclusions are based on the data and observations discussed in previous chapters. The data resulted from extensive testing of a variety of kiln dust, fly ash, and aggregate samples that are considered representative of the materials normally considered for use in pozzolanic road bases. However, these conclusions, and the test results upon which they are based, are not all-encompassing and certain sources of materials (or combinations of materials) may not behave according to the stated conclusion. Thus, these conclusions must be verified by evaluating specific sources of materials in accordance with locally applicable performance standards.

9.1 Characteristics and Quality of Kiln Dusts

9.1.1 General Observations on Kiln Dust

There is a great deal of variety between different sources of kiln dust. The major variables affecting kiln dust quality are the composition and proportions of the feed materials, type of kiln, kiln fuel, kiln efficiency, dust collection equipment, and whether some or all of the dust is recycled. Each source of kiln dust should be considered as having its own unique properties and, as such, should be analyzed.

However, based on analyses of successive daily grab samples for ten kiln dust sources, the dust collected from a particular kiln, if obtained during normal operating periods, will exhibit relatively consistent physical and chemical characteristics. Although the dust collected during normal kiln operations has been found to be reasonably consistent, the dust collected during kiln upset periods (start up, shutdown, change in kiln feed or fuel, etc.) could possibly be much more variable.

9.1.2 Cement Kiln Dusts

Kiln dusts collected from wet process plants will probably differ in character from dry process plant dusts. Generally, dry process kiln dust is more fine-grained and contains higher levels of free calcium oxide than the dust from wet process kilns. Some high sulfate and alkali levels were also observed in specific wet process kiln dusts.

The type of collection equipment affects kiln dust quality. Cyclones, being mechanical collectors, capture the coarser fraction of the dust stream. The character of precipitator dust varies depending on the location within the precipitation system, with the coarser particles captured first in the forward compartments and finer particles less easily captured in the later compartments. In baghouses, the character of the dust does not vary significantly from one compartment to the other compared to electrostatic precipitators.

Cement kiln dusts collected within certain sections of a dust collection system will be different from the dust collected from other sections. The upstream dust particles are coarser and contain more reactive calcium oxide than the downstream dust particles, which usually contain more alkalis. There are significant differences in the total dust from a cement plant compared to the separated dust. Downstream separated dusts contain less reactive calcium oxides than total dusts and are usually less suited to reacting with fly ash than are total dusts.

Cement kiln dusts may be divided into four groups:

Group I - Dry Total
Group II - Dry Separated
Group III - Wet Total
Group IV - Wet Separated

The relationship of compressive strength development to cement dust grouping is illustrated in Figure 13. These data indicate that Group I cement kiln dusts are the most reactive with fly ash, with the Group II and Group III dusts being somewhat less reactive, but comparable, and the Group IV dusts varying in reactivity over a wider range, but usually being the least reactive with fly ash.

9.1.3 Lime Kiln Dusts

Most of the lime kiln dust collected and available in the United States is from rotary kilns. Virtually all of the dust collected from lime production is disposed of or utilized, but not recycled. The dust available represents the total dust and is usually collected by baghouses with or without cyclones.

Lime kiln dusts are coarser in particle size than cement kiln dusts and are lower in specific surface. There are, in addition, significant differences in the characteristics of kiln dusts collected from the burning of high calcium limestone compared to dolomitic limestone. The former are higher in free lime and react more strongly when exposed to water, while the latter contain a combination of calcium and magnesium oxides and are more slowly reactive.

High calcium lime kiln dusts often contain high levels of free lime and are reactive in a similar manner to quicklime. A good indicator of the reactivity of lime kiln dusts is a temperature rise test. Lime kiln dusts which exhibit a rise in temperature greater than 20°C. (68°F.) have been termed Group H dusts, while lime kiln dusts with a temperature rise below 20°C. (68°F.) are termed Group L dusts.

Both classes of lime kiln dust react with fly ash, but the Group H dusts must be slaked with excess water, while the Group L dusts can be mixed with fly ash without the need for slaking. The slaking of Group H lime kiln dusts is often accompanied by a decline in the strength gain potential of the resulting hydrated dust with fly ash.

9.1.4 Stockpiled Kiln Dusts

In contrast to fresh kiln dust, the characteristics of aged stockpiled kiln dusts are highly variable and inconsistent. Aged kiln dust stockpiles may in some cases be contaminated with foreign matter unless the dusts are specifically set aside for later use. Stockpiled kiln dusts will not generally be as active as fresh kiln dusts, and may require beneficiation before use. Fresh kiln dusts can be conditioned with sufficient water to prevent dusting and stored above ground in stockpiles for several months. Such dusts can still be considered suitable for use after beneficiation, since their composition would be known and the short-term stockpiles can be kept free from contamination.

9.2 Chemical Analysis of Kiln Dusts

9.2.1 Cement Kiln Dust Chemistry

In addition to free lime, other chemical constituents are also considered of some importance in the analysis of cement kiln dust. It is known that many cement kiln dusts contain some unreacted or residual cement compounds, probably in the form of calcium silicates or aluminates. The presence of alkali was not found to be beneficial to strength development.

The presence of sulfates at relatively low levels (less than 5 percent) may be beneficial as a moderator, particularly when the kiln dust is used with a Class C or self-hardening fly ash. The presence of sulfates at relatively high levels (greater than 10 percent) is probably less beneficial, possibly even detrimental, although the results of the strength tests are inconclusive. There is, however, evidence that excessive sulfate in cement kiln dust is a contributing factor to poor durability or resistance to freezing and thawing in kiln dust-fly ash-aggregate compositions.

The higher the loss on ignition, the less reactive the kiln dust, since higher loss on ignition is indicative of higher levels of carbonation and lower levels of calcium in the oxide form. The presence of calcite in mineralogical analyses is concurrent with higher loss on ignition and the calcite is essentially non-reactive.

The presence of chlorides in cement kiln dusts is detrimental to pozzolanic reactivity. Although chloride levels were not identified in the characterization analyses, such levels are related to the extent of chloride control associated with preheater systems at some dry process plants.

9.2.2 Lime Kiln Dust Chemistry

The principal chemical differences in lime kiln dusts are between the high calcium and dolomitic dusts. The dolomitic dusts are characterized by comparatively lower calcium oxide contents with accompanying higher magnesium oxide contents.

Most lime kiln dusts contain little or no alkalis or sulfates, compared with the alkali and sulfate levels found in many of the cement kiln dusts. The sulfate levels of lime kiln dusts from coal-burning lime plants, which constitute the majority, can be expected to be higher than the sulfate levels from lime plants which burn oil or natural gas as fuel.

9.2.3 Stockpiled Kiln Dust Chemistry

Due to prolonged exposure to the elements, aged stockpiled kiln dusts are for all practical purposes lacking in available free lime content. As noted previously, the composition of aged stockpiled dusts can be expected to vary significantly, depending on the location within the stockpile. Weathering usually also results in the formation of agglomerations, expecially at the exposed surfaces, so that the resulting particle size of these stockpiled kiln dusts is considerable coarser than that of fresh dusts. Based on the samples tested in this program, aged stockpiled kiln dusts usually react poorly with fly ash.

Conditioning of both lime and cement kiln dusts produces an effect which is similar to that of short-term stockpiling. The free lime is converted to hydrate, some carbonation occurs and, in general, the reactivity of conditioned dust is diminished. With conditioned (or even aged stockpiled) dusts, the use of an activator may be needed to increase or enhance reactivity. Previous research (38) has demonstrated that the addition of relatively small amounts of caustic materials (lime slurry or sodium hydroxide) has resulted in significant increases in 7 day compressive strength of kiln dust-fly ash-aggregate compositions using aged or stockpiled kiln dust.

9.3 Strength Development of Kiln Dust-Fly Ash Combinations

The use of the pozzolanic activity tests with cube specimens, as described in ASTM C593, correlates very well with the free lime and fineness of kiln dust, which are two of the parameters which most directly affect kiln dust reactivity with fly ash. Pozzolanic activity tests may not, however, provide a satisfactory indication of the relative strength of a number of different kiln dust samples, particularly when used with different fly ashes and aggregates in pozzolanic base compositions.

Strength results of Carver specimens compacted to Proctor densities provide a good indication of the relative strengths of different kiln dust-fly ash strength test ratios. Results of Carver specimens provide a better indication of comparative strength development than of the actual value of the strength. There does not appear to be a good correlation between the strength values of kiln dust-fly ash Carver cylinders and the strength values of the same kiln dust and fly ash when blended with aggregate.

The strength development of kiln dust-fly ash combinations with sand aggregate, either in cube or Carver test specimens, is greater than the strength development of similar lime-fly ash combinations in most instances.

When kiln dusts are combined with fly ash, the strength development may be influenced as much by the fly ash as by the kiln dust. This is particularly true of the Class C western coal fly ashes, which may be hydraulic or self-hardening, as well as pozzolanic.

With few exceptions, fresh cement kiln dusts will work with nearly any fly ash to produce strengths as high or higher than those measured with commercial hydrated lime and fly ash. Total dusts, especially from dry process plants, usually produce the highest strengths. Separated dusts, particularly those from wet process plants, ordinarily result in the lowest strength development. Most lime kiln dusts also react with fly ash, although hydration of Group H (reactive) dusts can adversely affect strength development.

It is important to note that higher concentrations of kiln dust are required than those of normal hydrated lime. With most cement kiln dusts, maximum strengths are achieved using a 2:1 ratio of kiln dust to fly ash, although 1:1 ratios usually also result in acceptable strengths.

Most lime kiln dust-fly ash combinations achieve maximum strength at 1:1 kiln dust-fly ash ratios, although 1:2 ratios often develop comparable strengths. By contrast, lime-fly ash ratios normally range from 1:3 to 1:4 in most commercial lime-fly ash-aggregate mixes.

9.4 Strength Development of Kiln Dust-Fly Ash-Aggregate Combinations

In these combinations, strength development is influenced by three factors: the kiln dust, the fly ash, and the aggregate. The type of aggregate used in a mix can and does have a significant effect on the strength. Mixes containing the dolomitic limestone aggregate usually resulted in higher density and compressive strength than mixes containing the siliceous aggregates.

Most all of the kiln dust-fly ash-aggregate mixes tested in Task C had considerably higher strengths than the lime-fly ash-aggregate control mix at the optimum kiln dust-fly ash ratios. The effect of the fly ash on strength development of kiln dust-fly ash-aggregate mixes depends on the type of fly ash used in the mix. The data developed from this investigation strongly suggests that kiln dust-fly ash systems develop two different ranges of strength, depending on whether a Class C or a Class F fly ash is used. Use of Class C fly ash produces higher 7 day strengths than Class F fly ash.

For most Class F fly ashes, little change in strength results from using a different fly ash source, except for western bituminous fly ashes such as FA-4 and FA-17. Use of these types of fly ashes results in some improvement of mix compressive strength compared to normal Class F fly ash. However, the highest strength improvements were noted when Class C fly ashes were used. Use of Class C fly ash resulted in the highest strength development of Task C test mixes using the Group IV (wet separated) cement kiln dusts.

Use of the Class C fly ashes in pozzolanic road base compositions also involves an awareness of the need for special handling procedures. Most Class C fly ashes, expecially those with a high free lime content, set up rapidly when exposed to water. In order to avoid problems with mix compaction, conditioning or stockpiling of such fly ash may be required.

The use of total dusts (Groups I and III) results in higher ranges of compressive strength than separated dusts (Groups II and IV) and, in general, dry cement kiln dusts provide somewhat better strength performance in kiln dust-fly ash-aggregate mixes than wet cement kiln dusts. It is difficult to generalize on the strength development of lime kiln dusts, except that most Group H lime kiln dusts tested developed lower than expected strengths due to the slaking of high levels of free lime in these dusts.

The data presented in Table 24 and Figure 15 indicate that there is a relationship between the total reactive oxides of cement kiln dusts and the compressive strength of kiln dust-fly ash-aggregate test specimens. Because of higher levels of free lime, there is no such correlation for lime kiln dusts. The total reactive oxides can be simply estimated by the following formula:

$$\text{Reactive Oxides} = [(CaO+MgO) - LOI] + (K_2O + Na_2O)$$

where the alkalis ($K_2O + Na_2O$) should not exceed 6 percent.

If the value of the alkalines [(CaO+MgO) - LOI] is less than 12, or the total reactive oxide value is less than 18, the cement kiln dust in question may develop comparatively low strength and may not be suitable for use.

A study of compressive strength test results for kiln dust-fly ash-aggregate test mixes indicate that, depending on the class of fly ash used, there are four different ranges of 7-day compressive strength achieved by these mixtures:

	Class C	Class F
Poor	600 psi or less	400 psi or less
Fair	600 to 1200 psi	400 to 800 psi
Very Good	1200 to 2000 psi	800 to 1200 psi
Outstanding	Greater than 2000 psi	Greater than 1200 psi

Kiln dust-fly ash-aggregate mixes definitely gain in strength with age and are capable of developing extremely high compressive strength (2000 to 3000 psi), even when cured under ambient temperature conditions. In nearly all cases, the kiln dust-fly ash-aggregate mixes exhibited greater ultimate strengths than comparable lime-fly ash-aggregate mixes. Although the 7-day strengths of mixes containing Class C fly ash are higher than those containing Class F fly ash, the long-term (60 and 90 day) strengths of mixes with the two types of fly ash are comparable.

Based on the compressive strength data from this program, it is evident that the majority of the kiln dusts sampled and tested react with fly ash at optimum ratios to develop higher 7 day strengths than conventional lime-fly ash-aggregate mixes. These optimum ratios normally contain much higher concentrations of kiln dust to fly ash, compared to commercial lime. The improved early strength of kiln dust-fly ash-aggregate mixes may be beneficial for late season strength development, while possibly helping to extend the construction season for placement of stabilized base.

9.5 Other Engineering Properties of Kiln Dust-Fly Ash-Aggregate Combinations

In addition to compressive strength, the durability, volume stability, and autogenous healing characteristics of pozzolanic road base compositions are also of importance. All but three kiln dust-fly ash-aggregate compositions showed excellent durability. Weight losses in freeze thaw were all extremely low (2 percent or less) and closely compared with the weight loss values of similar lime-fly ash-aggregate control mixes. Of the three mixes failing the freeze-thaw test, two containing CD-6 performed poorly, while one containing CD-14 was marginal. Both kiln dusts (but particularly CD-6) contain higher than average levels of sulfate and alkali, together with a very low free lime content. Therefore, based on these test results, it appears that use of kiln dusts high in sulfate and alkali content will adversely affect mix durability.

Most kiln dust-fly ash-aggregate mixes are dimensionally stable over long periods of time (up to 90 days). Volume changes for kiln dust-fly ash-aggregate mixes are, for the most part, negligible and are of comparable magnitude to those of conventional lime-fly ash-aggregate compositions. Notable exceptions were mixtures containing CD-6 (a cement dust with an exceptionally high sulfate content) and LD-11 (a lime dust with a very high free lime content). When using dolomitic lime kiln dusts, the presence of periclase, as shown in a mineralogical analysis, can be detrimental to volume stability because its hydration and conversion to brucite is expansive.

Visual examination of kiln dust-fly ash-aggregate test specimens indicates that these compositions may not possess autogeneous healing properties to quite as great an extent as conventional lime-fly ash-aggregate mixtures. However, most kiln dust-fly ash-aggregate test specimens do tend to recement across cracking patterns and are capable of exceeding by a substantial percentage initial compressive strength following additional curing and retest.

Tensile strength and resilient modulus properties of kiln dust-fly ash-aggregate mixes are equal to or in most cases greater than comparable properties of lime-fly ash-aggregate mixes. For kiln dust-fly ash-aggregate mixes using Class C fly ash, the splitting tensile strength and resilient modulus properties are equivalent to a low strength portland cement concrete.

9.6 Overall Comparison of Kiln Dust-Fly Ash-Aggregate Mixes with Lime-Fly Ash-Aggregate Mixes

The test data developed in this study provides evidence that, with few exceptions, kiln dusts are capable of being substituted for hydrated lime in lime-fly ash-aggregate road base compositions. The possible exceptions are cement kiln dusts with high sulfate or alkali content or lime kiln dusts with very high levels of free lime.

Most kiln dust-fly ash-aggregate mixes develop somewhat higher early strength than conventional lime-fly ash-aggregate mixes, while providing equal or better durability and volume stability characteristics. The autogenous healing properties of kiln dust-fly ash-aggregate mixtures, while not quite as evident as those of lime-fly ash-aggregate mixtures, are still present and constitute an additional feature of the kiln dust-fly ash-aggregate system.

In general, the concentrations of kiln dust required are substantially higher than lime, meaning that greater quantities of kiln dust are needed to react with fly ash.

10. RECOMMENDATIONS

The list of recommendations presented below is based on a review of the technical data and conclusions presented earlier in this report, together with a review of published and unpublished data on kiln dust-fly ash systems, as well as discussions with producers and users of kiln dust in pozzolanic road base systems.

10.1 Evaluation of Kiln Dust Materials

Each kiln dust source must be thoroughly analyzed to determine its composition, physical properties, mineralogy, reactivity, and strength development with fly ash. Data from the kiln dust producer should be obtained and reviewed, but should not be used in lieu of performing confirming tests on representative samples of the kiln dust. A complete series of tests run on random daily grab samples is recommended in order to verify composition, range, and consistency, as well as mineralogy.

It is extremely important that kiln dusts be sampled only during normal periods of kiln operation. If at all possible, prospective users should avoid kiln dusts obtained during a kiln upset period. Every effort should be made to accurately determine where and when a sample of kiln dust was obtained and whether the sample is a total or a separated dust. This is of particular significance at cement plants, where dust separation for recycling is often practiced. At lime plants, it is recommended that only the dust from rotary kiln operations be sampled.

Where possible, aged stockpiled kiln dusts should be avoided and not used with fly ash as a component of a highway base material. However, short-term conditioning and storage of kiln dusts may be utilized as a means of alleviating resupply problems. The use of conditioned kiln dusts may, in many cases, necessitate the addition of commercial lime or other caustic material to enhance short-term strength development to desired levels.

For cement kiln dusts, a classification of the dust into one of four main groups should be made, based on the kiln type and whether or not the dust has been separated. The group of dust will provide some indication of the relative utilization potential of the dust sample. For lime kiln dusts, a temperature rise test, described earlier in the text, should be performed. The results of the temperature rise test will permit classification of the dust into one of two groups, based on the degree of heat released due to hydration of the free lime in the dust.

Extreme caution is recommended in the handling and use of Group H lime kiln dusts, both in the laboratory and in the field. These dusts contain appreciable levels of free lime and generally behave in a similar manner to quicklime. Therefore, the same precautions normally taken in the handling and use of quicklime should be employed with Group H lime kiln dusts.

When running pozzolanic activity tests on kiln dust-fly ash-sand cube specimens, a 28-day ambient strength determination is recommended for inclusion. Ambient 28-day strengths ranging from 150 to 200 psi or greater after

28 days are an indicator of the potential of a given source of kiln dust to react with a given source of fly ash.

Regardless of the extent of the analyses performed on any kiln dust sample, a final decision concerning its potential for use as a pozzolanic base material should be made after performing a series of compressive strength screening tests using Proctor test cylinders, as described in the following section.

10.2 Mix Design Recommendations

The following recommendations are made to assist prospective users of kiln dusts in evaluating kiln dusts and in determination of mix proportions and engineering properties of pozzolanic base course compositions containing either cement or lime kiln dusts.

10.2.1 Kiln Dust Screening Tests

A number of steps should be taken to establish the suitability of a given source of kiln dust for use with fly ash as a pozzolanic base material. Initially, available physical and chemical data on the kiln dust, fly ash, and aggregate sources should be obtained and evaluated prior to further testing. In the case of cement kiln dusts, the total reactive oxides (alkaline and alkali) and the free lime content of the dust should be determined. For lime kiln dusts, the free lime content will in most cases be a reasonably good indicator of potential for strength development.

Where possible, cement kiln dusts having greater than 10 percent sulfate or alkali content should be avoided or their behavior in a pozzolanic road base system should be very carefully monitored. Group H lime kiln dusts with a free lime content greater than 20 percent should be used with utmost care. Construction procedures for mixing and placement should be based on European experiences or recommended practices developed by the National Lime Association for the use of quicklime in stabilization projects.

The most practical screening test is a determination of strength development, involving the preparation of Proctor-size test specimens in accordance with ASTM C593. Suggested proportions for an initial screening test should involve the preparation of a trial mix containing 76 percent local aggregate, with the remainder of the mix being kiln dust and fly ash. The aggregate should meet applicable local gradation requirements. Recommended kiln dust-fly ash proportions will depend on the type and characteristics of the dust sample. Because lime dusts usually contain more free lime than cement dusts, general guidelines for kiln dust-fly ash proportions are:

Cement Kiln Dust - use kiln dust-fly ash ratios of 2:1 and 1:1
Lime Kiln Dust - use kiln dust-fly ash ratios of 1:1 and 1:2.

The test specimens must be compacted according to ASTM C593 procedures as close as possible to optimum moisture content. Three test specimens must be prepared for each of the test mixes. The test specimens must be cured in sealed cans for a period of 7 days at 38°C. (100°F.), then broken in compression. A 7-day compressive strength of 400 psi is considered a minimum value for acceptance of the kiln dust with Class F fly ash. If the test mix(es) have 7-day compressive strength(s) substantially less than 400 psi, the kiln dust should not receive further consideration for use in kiln dust-fly ash-aggregate pavement base materials, without modifications. When using a Class C fly ash, a 7-day compressive strength of 600 psi is recommended as the minimum value for acceptance because of the more rapid early strength gain characteristics typical of Class C fly ashes.

10.2.2 Kiln Dust-Fly Ash-Aggregate Mix Design

The design of kiln dust-fly ash-aggregate mixes should follow as closely as possible the mix design procedures established for lime-fly ash-aggregate mixtures. Once it has been determined from the screening test that a particular source of kiln dust is a promising candidate for use with fly ash and aggregate, the fines content resulting in maximum dry mix density must be established. Suggested fines additions of 15 to 30 percent are recommended for investigation. A curve of dry density vs. percent fines should be prepared in order to select an optimum fines content.

Once the optimum fines content has been determined, the moisture-density relationship of the component materials at this fines content must be established. This can be done by performing Proctor tests, one for each anticipated kiln dust-fly ash ratio. When testing Group H lime kiln dusts, it is important to maintain a condition of excess moisture in order to permit complete hydration of the free lime. A separate slaking test must be performed in advance in order to establish the required range of slaking water. The additional moisture should be added to the mix even though the resulting moisture content is in excess of the optimum moisture, since mixes containing reactive lime or cement dusts should be molded at optimum reactivity.

Following establishment of optimum moisture content(s) for molding of mixes, the strength of the test mixes can be determined. In addition to compressive strength development after 7-day curing at 38°C. (100°F.), the compressive strength after 14 days curing at 23°C. (73°F.) should also be tested. At least three kiln dust-fly ash proportions are recommended for each fines content. The recommended mix design is that mix resulting in the highest 7-day compressive strength.

In addition to strength development testing, the durability and volume stability of the selected kiln dust-fly ash-aggregate mix design must be investigated. The vacuum saturation test procedure (ASTM C593) and the freeze-thaw test (ASTM D560) should both be used for this evaluation. Volume stability should be determined using the autoclave expansion test (ASTM C151) or the mortar bar method (ASTM C490). The volume stability of any kiln dust-fly ash-aggregate mix using a dolomitic lime kiln dust should be very carefully checked prior to use.

Test mixes achieving poor compressive strengths should be tested immediately for durability and, if unable to pass either the vacuum saturation or freeze-thaw test, should be considered no further for use as a base material for highways. Poor compressive strength would be 400 psi or less with Class F fly ash and 600 psi or less for Class C fly ash.

Test mixes achieving fair compressive strength should also be tested for both durability and dimensional stability. If unable to pass the durability test, investigate the possibility of lime slurry or other caustic addition to improve strength development and then retest for durability. If unable to pass the dimensional stability test, do not consider for use as pozzolanic base.

Test mixes achieving very good strength should be checked for durability by vacuum saturation testing only. If able to pass vacuum saturation testing with little or no loss in 7-day strength, freeze-thaw testing is not considered necessary. However, these mixes must be analyzed for dimensional stability and, if they prove to be expansive (volume change greater than 1.0 percent), they should either not be used in pozzolanic base or should be used with great care and closely monitored.

Test mixes achieving excellent strength development need not be evaluated for durability. However, a check of dimensional stability should still be made. In the unlikely event such mixes show some expansion, modifications in mix design to use lower percentages of kiln dust are recommended. Excellent compressive strength would be greater than 1200 psi for Class F fly ash and greater than 2000 psi for Class C fly ash.

10.3 Logistical Considerations

During the development of mix design proportions, the amount of available kiln dust must be considered. For example, a 7.3 meter (24 foot) wide roadway with a base course 203.2 centimeters (8 inches) thick would require an estimated 6,600 tonnes (6,000 tons) of base material for a length of 1.6 kilometers (1 mile). If 76 percent aggregate is used in the mix design and a 2:1 kiln dust-fly ash ratio is recommended, this will involve 16 percent kiln dust and require 1,056 tonnes (nearly 1,000 tons) of kiln dust per 1.6 kilometers (1 mile). If there are limited quantities of kiln dust available, it may be advisable to modify the kiln dust-fly ash ratio to 1:1, which would only require 792 tonnes (about 700 tons) of kiln dust per 1.6 kilometers (1 mile). If strengths and other engineering properties are acceptable, kiln dust quantities can be conserved by 165 tonnes per kilometer or 300 tons per mile.

If fresh kiln dust is being used, it must be stored in enclosed bins or silos to keep out moisture and prevent dusting. Kiln dust can also be stockpiled and used with fly ash, provided it is conditioned with moderate amounts of water. The use of conditioned kiln dust and fly ash allows greater quantities of both materials to be set aside for future use without the need for enclosed storage. However, conditioning of kiln dust will cause either partial or complete hydration of the available calcium oxide component in the dust and may require the addition of some commercial hydrated lime to improve early strength development.

10.4 Mixing and Placement Considerations

Most kiln dusts, particularly cement kiln dusts, are very fine-grained and have very high specific surface values. Consequently, when stored in bins or silos, the fine-grained kiln dusts may have a tendency to clump or bridge together at the feed opening. Prospective users of kiln dusts are cautioned that bins or silos containing these materials should be equipped with vibration devices in order to minimize bridging or dislodge clumps at the feed opening. This is another reason for trying to design kiln dust-fly ash-aggregate mixes with the lowest practical kiln dust-fly ash ratio.

Compressive strength data developed during this program provides evidence that many kiln dust-fly ash-aggregate mixes develop compressive strength more rapidly than conventional lime-fly ash-aggregate mixes. Therefore, it is important that kiln dust-fly ash-aggregate mixes be placed and compacted within a reasonable time frame after mixing. These compositions cannot be stockpiled after mixing because they will harden within a period of hours. If Class C fly ash is used, it is possible that setting could occur within a matter of minutes because of the self-hardening nature of such fly ashes. Class C fly ashes may need to be conditioned prior to use. As a precaution, kiln dust-fly ash-aggregate mixes using Class C fly ash should be placed and compacted as soon as possible after mixing.

In order to reduce or eliminate the potential for expansion or detrimental volume changes, it is suggested that no kiln dust be used which has a high sulfate content (greater than 10 percent). A similar recommendation is made for avoiding the use of high alkali cement kiln dusts (combined $K_2O + Na_2O$ in excess of 10 percent). If a decision is made to utilize such dusts, they should be used only with the utmost caution.

The use of Group H lime kiln dusts having exceptionally high percentages of available or free lime (20 percent or more) should also be used with extreme caution. There is normally a need to condition or hydrate such dusts before or during mixing. Hydration of high percentages of free lime in these dusts is an exothermic process, usually accompanied by substantial release of heat and steam. If a Group H lime kiln dust is used, it is possible that the free lime component may only be partially hydrated and further hydration after mixing could cause expansive reactions which may result in detrimental long-term volume changes. Therefore, kiln dusts with a high free lime content (and indeed all dusts) should be handled with the same care as quicklime.

Although cement kiln dusts from alkali bypass systems were not sampled and tested during this program, it is known that such dusts are high in free lime and alkali content and could pose special problems in handling or mixing. Therefore, it is recommended that such alkali bypass dusts either be avoided or used with extreme caution.

11. REFERENCES

1. Meade, Richard K., Portland Cement: Its Composition, Raw Materials, Manufacture, Testing and Analysis., Third Edition, Chemical Publishing Company, Easton, Pa., 1926.

2. Boynton, Robert S., Chemistry and Technology of Lime and Limestone., John Wiley and Sons, Interscience, New York, New York, 1966.

3. "Lime Calcining Equipment and Systems", Kennedy Van Saun Corporation.

4. Portland Cement Association, Skokie, Illinois.

5. National Lime Association, Arlington, Virginia.

6. Davis, Thomas A. and Hooks, Don B., "Utilization of Waste Kiln Dust from the Cement Industry", Proceedings of the Fourth Mineral Waste Utilization Symposium, Chicago, Illinois, May, 1974.

7. National Lime Association, Second Kiln Dust Disposal Survey, Arlington, Virginia, June 23, 1977.

8. Guttschick, Kenneth, National Lime Association, Private Communication.

9. Hunt, Robert G. et al, "Development of Guidelines for Procurement of Highway Construction Products Containing Recovered Materials", Final Report, EPA Contract No. 68-01-6014, Washington, D.C., 1981.

10. Davis, T.A. and Hooks, D.B., "Study of the State of the Art of Disposal and Utilization of Waste Kiln Dust from the Cement Industry", Report of U.S. EPA, Grant No. R-801872, Southern Research Institute, Birmingham, Alabama, 1974.

11. American Society for Testing and Materials, Standard Specification C593-76a, "Fly Ash and Other Pozzolans for Use with Lime", ASTM Book of Standards, Part 13, 1980.

12. National Ash Association, Washington, D.C.

13. Hunt, et al, Op. cit.

14. Nicholson, J. Patrick, "Mixture for Pavement Bases and the Like", United States Patent No. 4, 018, 617, April 19, 1977.

15. Nicholson, J. Patrick, "Mixture for Pavement Bases and the Like", United States Patent No. 4, 038, 095, July 26, 1977.

16. Nicholson, J. Patrick, Chief Executive Officer, N-Viro Energy Systems, Ltd., Toledo, Ohio, Private Communication.

17. Minnick, L. John, "Reactions of Hydrated Lime with Pulverized Coal Fly Ash", Proceedings, First Ash Utilization Symposium, U.S. Bureau of Mines Information Circular No. 8318, Pittsburgh, Pa., 1967.

18. Greenberg, Sidney A., "The Chemisorption of Calcium Hydroxide by Silica", Journal of Physical Chemistry, March, 1956.

19. Terrel, Ronald L.; Epps, Jon A.; Barenberg, Ernest J.; Mitchell, James U.; and Thompson, Marshall R., "Soil Stabilization in Pavement Structures. A User's Manual. Volume 2 - Mixture Design Considerations", U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-IP-80-2, Washington D.C., 1979.

20. Ahlberg, Harold L. and Barenberg, Ernest J., "Pozzolanic Pavements", University of Illinois, Engineering Experiment Station, Bulletin No. 473, Urbana, Illinois, 1965.

21. Minnick, L.J.; Webster, W.C.; and Purdy, E.J., "Prediction of Fly Ash Performance", Proceedings of Second Fly Ash Utilization Symposium, U.S. Bureau of Mines, Information Circular No. 8488, Pittsburgh, Pa., 1970.

22. Barenberg, Ernest J. and Thompson, Marshall R., "Lime-Fly Ash Stabilized Bases and Subbases", National Cooperative Highway Research Program, Synthesis of Highway Practice No. 37, Transportation Research Board, Washington, D.C., 1976.

23. Taylor, H.F.W., "The Chemistry of Cements", Academic Press, New York, New York.

24. American Society for Testing and Materials, Standard Specification C618-80, "Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete", ASTM Book of Standards, Part 14, 1981.

25. McKerall, William C.; Ledbetter, W.B.; and Teague, David J., "Analysis of Fly Ashes Produced in Texas", Report No. FHWA/TX 81/21 & 240-1, Texas State Department of Highways and Public Transportation, Austin, Texas, 1981.

26. Fletcher, W.K., "Analytical Methods in Geochemical Prospecting", Elsiviere Scientific Publishing Company, New York, New York, 1981.

27. Sell, Nancy J. and Fischbach, Fritz, "Dust Return to Rotary Kilns", University of Wisconsin - Green Bay, Report to Allis-Chalmers, Green Bay, Wisconsin, November, 1974.

11. REFERENCES (Continued)

28. Nicholson, J. Patrick, N-Viro Energy Systems, Ltd., Toledo, Ohio, Private Communication.

29. Pachowski, Jan et al, "The Application of Brown Coal Fly Ash to Road Base Courses", U.S. Department of Transportation, Federal Highway Administration, and Polish Ministry of Transport, Warsaw, Poland, Report No. FHWA-RD-79-101, Washington, D.C., September, 1979.

30. American Society for Testing and Materials, Standard Specification D2940-74, "Graded Aggregate Material for Bases or Subbases for Highways or Airports", ASTM Book of Standards, Part 19, 1982.

31. "Cement Treated Aggregate Base", Special Report No. 221,015, Portland Cement Association, Skokie, Illinois, 1979.

32. Kneller, William A., Director, Eitel Institute for Silicate Research, Unpublished Laboratory Report No. 44 to N-Viro Energy Systems, Ltd., Toledo, Ohio, 1982.

33. Thornton, Sam I. and Parker, David G., "Construction Procedures Using Self-Hardening Fly Ash", U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA/AR/80/004, 1980.

34. Nicholson, J. Patrick, N-Viro Energy Systems, Ltd., Toledo, Ohio, Private Communication.

35. Turpin, Raymond C., Jr. "Pozzolan Cement Compositions", United States Patent No. 4,256,500, March 17, 1981.

36. Barenberg, Ernest J. and Thompson, Marshall R., "Evaluation of Pavement at Sherwin-Williams Plant Entrance", Report prepared for N-Viro Energy Systems, Ltd., December, 1980.

37. Miller, Cass T.; Bensch, Dennis G.; and Colony, David C., "Pozzolanic Concrete Base Courses Using Cement Kiln Dust and Fly Ash", 59th Annual Meeting of Transportation Research Board, Washington, D.C., January, 1980.

38. Brochel, Donald J., Ritchie Laboratories, Unpublished Report on the Behavior of N-Viro Crete Paving Methods, Wichita, Kansas, 1982.

39. American Society for Testing and Materials, Standard Specification D560-57, "Freezing and Thawing of Compacted Soil-Cement Mixtures", ASTM Book of Standards, Part 19, 1982.

40. Dempsey, Barry J. and Thompson, Marshall R. "Vacuum Saturation Method for Predicting Freeze-Thaw Durability of Stabilized Materials." Highway Research Board, Record No. 442, Washington, D.C., 1973.

11. REFERENCES (Continued)

41. Brown, L.S. and Sawayze, M.A. "Autoclave Tests and The Microscope." Rock Products, Vol. 41, No. 6, 1938.

42. Reshi, S.S. and Majumdar, A.J. "High Magnesia Portland Cements: Studies on Cements Prepared with Reagent Grade Chemicals." Building Research Establishment, Current Paper No. CP 12/70, Garston, Watford, England, 1970.

43. Kneller, William A. Unpublished Laboratory Report No. 82720 to N-Viro Energy Systems, Inc., Toledo, Ohio, 1982.

44. American Society for Testing and Materials, Standard Specification D3497-79, "Dynamic Modulus of Asphalt Mixtures", ASTM Book of Standards, Part 15, 1982.

APPENDIX I - KILN DUST SAMPLING PROCEDURE

The United States Department of Energy and the United States Department of Transportation, Federal Highway Administration, are co-sponsoring a research program entitled "Kiln Dust-Fly Ash Systems for Highway Bases and Sub-bases." This program requires the characterization and experimental use of kiln dusts covering a cross-section of the cement and lime industry. No data developed will be disclosed in any way such that an individual plant can be identified, without that plant's approval. Given the possible variation in kiln dust characteristics during production, and the need to avoid influences such as carbonation, the following sampling notes have been developed as suggested guidelines.

Sampling Point(s)

All kiln dust samples should be taken at the point where the kiln dust is discharged for disposal and/or is available for outside applications. Following evaluations of available chemical data, and the details of dust collection and discharge systems at a particular plant, the location of a specific sampling point (or points) for that plant will be identified by Valley Forge Laboratories and Trow, Ltd.

Sampling Period and Frequency

It is desirable to obtain a composite sample taken over a reasonable production period. To comprise the composite sample, a set of 15 individual 20-pound samples will be taken once a day over a 15-day period. All 15 of these samples will be taken from the same designated sampling point. For those plants where more than one sampling point is desired, an independent set of 15 samples must be obtained from each sampling point.

Sampling Procedure

1. The individual 20-pound samples should be taken in the same way as grab samples of cement or lime are taken at the plant. (ASTM C183-78 for instance.)

2. As individual samples are taken, they should be placed in double, moisture-proof multiple-wall paper bags or plastic bags. Care should be taken to seal the bags immediately after filling, eliminating excess air and avoiding moisture absorption and aeration of the sample.

3. Each 20-pound sample should be clearly identified with the producer's name, kiln dust type and source, sampling point, sampling date and sampling time.

4. For shipping to Valley Forge Laboratories, Inc. at the end of the two week sampling period, the 15 individual 20-pound samples from a discharge point should be packed in a suitable, strong container such as a steel drum. (Sampling bags and shipping drums can be supplied if necessary.)

Chemical Testing

If possible, it would be most helpful if a standard kiln dust (cement or lime) chemistry and fineness test of the type normally followed at the plant could be completed and supplied for each individual 20-pound sample. After review of available chemical data from each plant, Valley Forge Laboratories and Trow, Ltd. will contact the plant chemist and any other individual responsible for obtaining the dust sample in advance of sampling to work out the details of such tests.

Sampling Times

The sampling times for the 15 individual 20-pound samples should be based on some random method. A suggested method is attached that may be helpful.

It should be noted that samples should not be taken immediately following the repair or adjustment of manufacturing equipment and processes, or from inappropriate places, as it is important that the samples represent the typical kiln dust production. Under no circumstances should sampling be done within 24 hours of an upset in a particular kiln.

Desired Time Period of Sampling

At this time, it is desirable, wherever possible, to conduct the sampling of kiln dusts during the month of August, 1981. In order to adhere to this proposed sheduling, it is requested that available chemical data for various dust streams at each plant, plus a schematic of dust collection and disposal systems for each plant, be forwarded to Valley Forge Laboratories as soon as possible to allow time for sampling point identification.

Samples from Stockpiles (Selected Plants Only)

A few plants will be requested to supply samples from stockpiled kiln dust. The procedures for this sampling will be developed with the plants selected.

YOUR ASSISTANCE IS MOST APPRECIATED!

Suggested Random Sampling Method

Samples must be unbiased if they are to be reliable. A biased sample would be one taken because it looks "about right", or because it is easiest to get to; or one taken when the plant is not running normally. Sampling must not be swayed by judgments of the expected result of the test. Also, the sample must be taken so that it is representative. A random sample will satisfy all of these conditions.

The simplest way to do this is to place slips of paper, each numbered for one of the availble shifts over the two-week sampling period, in a box. Then draw 15 slips from the box giving the 15 shifts to be sampled.

To determine the sampling time within each of the 15 shifts, place slips of paper, each with a period of time available (possible hourly) during a shift (i.e. 0 to 1 hr., 1 to 2 hrs., 2 to 3 hrs., etc.), in a box. Then draw one slip from the box giving the sampling time within the shift. (The slip should be returned to the box before drawing the sampling time for the next shift.)

The above will give a list of shifts to be sampled and sampling times. If a shift or time is impossible to sample for some reason, another shift or time should then be selected by the above procedure.

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.[*]

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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[*] The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.