FINAL TECHNICAL REPORT
November 1, 2000, through October 31, 2001

Project Title: **IMPLEMENTATION OF TECHNOLOGY FOR CONTROLLED LOW-STRENGTH MATERIALS USING ILLINOIS COAL COMBUSTION PRODUCTS**

ICCI Project Number: 00-1/3.1B-5
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ABSTRACT

Over 90% of 5.5 million tons per year of coal ash produced from burning Illinois coal is currently disposed in landfills. The focus of this project was to develop a high-volume Illinois coal ash content controlled low-strength material (CLSM) (a.k.a. flowable slurry). The CLSM slurry manufactured as a part of this project consisted of very low amounts of cement, high-volumes of Illinois coal ash, and water to produce flowable slurry for many construction applications. Use of CLSM as a construction material would consume large amounts of Illinois coal ash providing economic as well as ecological benefits. Illinois Department of Transportation (IDOT) and other currently available construction specifications from Illinois were used for manufacturing CLSM in Rockford and Peoria at ready-mixed concrete/CLSM manufacturing plants.

Two series of CLSM were batched in the laboratory, Series 1 CLSM mixtures were composed of a fine crushed sand, Illinois coal ash, and cement. The second series (Series 2) was composed of a combination of typical concrete sand, Illinois coal ash, and cement. Mixtures for both series varied the coal ash and sand content from 0% Illinois coal ash, and 100% sand or fine crushed sand, to 100% coal ash without sand. Laboratory mixtures were evaluated for fresh CLSM properties as well as compressive strength and water permeability. The laboratory mixtures were then used as the basis for mixture proportions used for field manufacturing. Series 1 field mixtures were manufactured at the facilities of Meyer Material Co. and Rockford Sand and Gravel, Inc., Rockford, IL; while Series 2 field mixtures were manufactured at the facilities of the United Ready-Mix, Inc., Peoria, IL. The CLSM test mixtures manufactured generated the necessary experimental and production data to optimize CLSM mixture proportions for commercial production. Two construction demonstration/technology transfer workshops were held in Illinois. One field demonstration was held in Rockford, IL, in cooperation with the Rockford Blacktop Construction Co., and a second demonstration and technology transfer workshop was held in Peoria, IL with cooperation from the United Ready-Mix, Inc.

EXECUTIVE SUMMARY

Approximately 5.5 million tons of coal combustion products are generated each year from combustion of Illinois coal. About 3.0 million tons of these coal combustion products are produced in Illinois and the remaining 2.5 million tons are generated in other states (including Wisconsin) burning Illinois coal. A majority of these 5.5 million tons of ash products are landfilled. The overall utilization rate in the USA for all coal ashes was approximately 30% in 1999 (i.e., about 30 million tons). Illinois coal, when it is burned in conventional boilers, produces Class F, low-lime, fly ash. In general, utilization rate of Class F fly ash in U.S.A. is substantially lower relative to Class C, high-lime, fly ash. This is partly due to the perceived lower quality of Class F fly ash compared to Class C fly ash, and greater variation in its properties, especially for the fly ash generated from older power plants. Also, there is a significant lack of commercial products that use high-volumes of Class F fly ash; and, there is even a greater lack of use for clean coal ash. Due to shrinking landfill space, to solve environmental concerns, and due to increased public awareness and debate, it has become mandatory to find practical solutions to this "ash problem".

The objective of this project was to implement technology and development of markets for controlled low-strength material (CLSM) slurry for use in Illinois using Illinois coal ash as the main component, meeting Illinois regulations, for use by Illinois state agencies, and others, especially Illinois Department of Transportation (IDOT). Use of significant quantities of Illinois coal ash in CLSM slurry will result in reduced costs to users of Illinois coal. The CLSM mixtures developed for this project used a wet-collected Class F coal ash obtained from Pekin, IL. CLSM slurry may be used wherever a typical compacted backfill material is used such as for pavement sub-base, utility trenches, backfill around foundations, foundation base materials, etc. The Illinois Department of Transportation (IDOT) has developed and written specifications for use of CLSM slurry and general acceptance criteria. Some county highway departments already accept the IDOT specifications and allow CLSM use for backfilling utility trenches. Many potential Illinois users and producers of CLSM slurry have not been familiar with the many advantages of CLSM over traditional backfill materials. The existence of approved Illinois specifications on CLSM, and considerable existing literature on CLSM containing high-volumes of fly ash, indicate that CLSM slurry may not need additional research dollars. However, to meet the objectives of market development and to promote the use of Illinois coal ash and production technology of CLSM slurry, this project focused on bringing the technology to ready-mixed concrete plants with construction demonstrations and technology transfer workshops showcasing the use of Illinois coal ash in CLSM slurry. Two technology transfer workshops were held in Illinois, one in Rockford and the second in Peoria. The target audience for these implementations, workshops, and construction demonstrations were those that would produce, use, and specify CLSM, such as ready-mixed concrete plant operators, engineers, contractors, government engineers, etc.

The work for this project involved production-scale manufacturing, testing, and

evaluation of selected mixtures under actual commercial production facilities, followed by technology transfer workshops and construction demonstrations. The results of the project were intended to establish mixture proportions and production technology for CLSM mixtures containing Illinois coal ash that meets IDOT specifications for many varied applications. In order to establish performance characteristics of CLSM prior to prototype-scale production, laboratory mixtures were produced. Two separate series of mixtures, Series 1 which used fine crushed sand (FCS) as the fine aggregate, and Series 2, which used standard concrete sand as the fine aggregate. Series 1 laboratory mixtures consisted of two groups of mixtures: Series 1A, which established preliminary performance data, and Series 1B, which had more extensive testing.

A total of six mixtures were produced for Series 1A mixtures. Fly ash content of the mixtures, expressed as a percentage of total fines (fly ash and crushed fine sand), varied from 100% (Mixture S1) to 0% (Mixture S6). Intermediate fly ash concentrations were established at 80%, 50%, 40%, and 27% for Mixtures S2, S3, S4, and S5, respectively. Compressive strength of all mixtures were tested at the age of 7, 28 and 182 days. All mixtures exhibited satisfactory levels of compressive strength (less than 100 psi at 28-days). Mixtures with lowest cement content produced the lowest strength.

Based upon the results of Series 1A, five Series 1B mixtures were produced. Similar to the Series 1A mixtures, ash content of the mixtures varied from 100% (Mixture A1) to 0% (Mixture A5). Target values for ash content of mixtures were 67% for Mixture A2, 50% for Mixture A3, and 33% for Mixture A4. Flow of the mixtures was maintained at about ten inches. Water requirement of the mixtures decreased with increased fine crushed sand content, 919 lb/yd^3 for Mixture A1 (100% ash) to 518 lb/yd^3 for Mixture A5 (0% ash). As expected, density of the CLSM also increased as the amount of fine crushed sand increased: 90 lb/ft^3 to 134 lb/ft^3 for Mixtures A1 to A5. Compressive strength of the mixtures were determined at the ages of 3, 7, 28, 56, 91 and 130 days. Initially, at the age of 3 days compressive strength of mixtures varied between 20-35 psi. Compressive strength of the mixtures typically increased at later ages. Dynamic cone penetrometer (DCP) values, for all mixtures were one inch/blow or less at the age of 24 hours. IDOT CLSM specifications indicate that 1.5-in/blow or less as adequate to support construction loading.

The second series of laboratory CLSM mixtures, Series 2, consisted of mixtures using standard concrete sand in combination with Illinois coal ash. Similar to Series 1 mixtures, the ash content of the mixtures was varied from 100% to 0% (ash content expressed as a percentage of total fines, ash and fine aggregate). A total of five mixtures were produced for Series 2. Mixture L1, 100% Illinois coal ash, was taken as the same mixture from Series 1, Mixture A1. Fly ash concentrations of Mixtures L1 to L6 was 100%, 81%, 60%, 40%, 20% and 4% respectively. Compressive strength of the mixtures were determined at the ages of 3, 7, 28, 56, and 91 days. Compressive strength of all mixtures was satisfactory for CLSM applications when the material may be excavated in the future (less than 100 psi at the age of 28 days). Mixtures L5 and L6 achieved the lowest strength, 10 to 15 psi at 56 and 91 days. Although low, a 10 psi unconfined compressive strength is equivalent to 1,440 lb/ft^2 for soil backfill. Typically this level of strength is acceptable for many backfill applications. Water permeability of the mixtures for Series 2 were slightly higher than Series 1 mixtures.

Prototype-scale production of CLSM was manufactured at the facilities of Meyer Material Company and Rockford Sand and Gravel, Inc. (Series F1), Rockford, IL, and at United Ready-Mix, Inc. (Series F2), Peoria, IL. Production at Meyer Material Co., and Rockford Sand and Gravel Inc., consisted of eight CLSM mixtures using a combination of Illinois coal ash and fine crushed sand as the fine aggregate. The purpose of the prototype production at these facilities was to familiarize the producers with the handling of Illinois coal ash for CLSM and to obtain test data from these production mixtures. The first series of prototype production mixtures, Series F1, consisted of five mixtures, 1 to 5, containing 100%, 64%, 47%, 23%, and 0% fly ash, respectively. Since several of the Series F1 mixtures fell outside of the expected range of laboratory mixtures, three additional prototype-scale mixtures were produced, Series F1A. Series F1A Mixtures 6, 7, and 8 contained 68%, 51%, and 33% fly ash, respectively. Approximately three cubic yards were produced for each prototype-scale mixture. Compressive strength of Series F1A mixtures was determined at the age of 7, 28, and 160 days. Compressive strength of Mixtures 6 and 7 were approximately the same: 25 to 30 psi at the age of 7 days, 50 psi at 28 days, and 90 to 100 psi at 160 days. Both of these CLSM mixtures are considered excavatable. Mixture 8, 33% fly ash and 67% fine crushed sand, attained a slightly higher compressive strength compared with Mixtures 6 and 7.

CLSM produced at the facilities of United Ready-Mix, Peoria, IL used coal ash and standard concrete sand as the fine aggregate. These CLSM mixtures, Series F2, consisted of six mixtures, Mixtures F1 to F6, which contained 100%, 83%, 50%, 43%, 20%, and 4% coal ash, respectively (expressed as percentage of total fines in the mixture, fly ash and standard concrete sand, Table 19). Compressive strength of Series F2 mixtures was measured at the ages of 8, 28, and 100 days. Compressive strength of Series F2 CLSM mixtures typically increased as the amount of fly ash was increased in the mixture. A significant increase was obtained at all test ages, particularly at the age of 100 days.

The CLSM test mixtures manufactured in Rockford and Peoria generated the necessary experimental and production data to optimize CLSM mixture proportions for commercial production. Two construction demonstration/technology transfer workshops were held in Illinois. In order to promote the use of CLSM using Illinois coal ash, two different geographic locations were selected in Illinois. One field demonstration was held in Rockford, IL, in cooperation with the Rockford Blacktop Construction Co., and a second demonstration and technology transfer workshop was held in Peoria, with cooperation from the City of Peoria. Also, as a part of these workshops, handout materials were developed for CLSM products, construction methods and technologies, for commercial and government use. In conjunction with these field demonstrations, a one-day workshop (in Rockford and Peoria) was held to introduce engineers, area contractors, ready-mixed concrete suppliers, environmental agencies, local and state government personnel, and other potential users to the benefits of CLSM slurry with Illinois coal ash.

OBJECTIVES

This project was proposed to provide a practical solution to "disposal problems" for Illinois coal combustion products. The primary goal of this implementation and market development project was to develop CLSM products for commercial manufacturing and everyday construction applications. In order to accomplish this, field investigations were needed. The main objective of this project was to develop CLSM for use in Illinois, using Illinois coal ash as the main component, meeting Illinois regulations, for satisfying the demands of Illinois state and other government units as well as private construction, for controlling costs of Illinois coal producers and users. The CLSM slurry developed for this project consisted of cement, water, and high-volumes of Class F coal ash obtained from a source in Illinois. This CLSM produced/developed may be used wherever a typical compacted sand backfill material is used such as for pavement sub-base, utility trenches, backfill around foundations, foundation base materials, etc. Cost for producing the CLSM is expected to be low since the amount of cement, which is the major cost component (about $80 per ton delivered) in the production of CLSM, is very small (about three percent of total materials). The use of CLSM as a backfill material is also significantly less labor intensive than conventional fill materials. When CLSM is used as a backfill material such as in utility trenches, costs associated with achieving the desired compaction, compared with other fill materials, is totally eliminated.

The work for this project involved production-scale manufacturing, testing, and evaluation of selected mixtures under actual commercial production facilities, followed by technology transfer workshops and construction demonstrations. The results of the project were intended to establish mixture proportions and production technology for Illinois coal ash CLSM mixtures that meets IDOT specifications for commercial applications. Specific goals established for this project were as follows.

(1) Conduct prototype-scale and manufacturing-scale field production of CLSM and construction demonstration projects, including physical, mechanical, and chemical characteristics of the field produced CLSM.

(2) Provide hands-on help and guidelines to ready-mixed concrete plants to manufacture CLSM and help develop mixture proportions for production of Illinois coal ash CLSM meeting the Illinois Department of Transportation specifications.

(3) Provide trouble-shooting help to CLSM producers for manufacturing CLSM for actual construction projects, including help them prepare construction bids and supporting documents for use of CLSM in any construction projects.

(4) Conduct technology transfer seminars for Illinois coal ash use in CLSM in Illinois. Provide practical production and construction information to potential users, producers, engineers, owners, power plant operators, government engineers, and others, regarding CLSM. Prepare information

on various options for use, mixture proportioning, and results of field demonstration projects.

In order to expose the technology of manufacturing and use of CLSM using Illinois coal combustion products, two different geographic locations in Illinois (Peoria and Rockford) were selected for the field demonstrations and technology transfer workshops. One field demonstration was held in Rockford with cooperation of the Rockford Blacktop Construction Co. The second demonstration and technology transfer workshop was held in Peoria, with cooperation from the City of Peoria. As a part of this phase, specifications and/or manuals for adoption of CLSM products, construction methods and technologies, for commercial and government use, were developed. In conjunction with these field demonstrations, a one-day workshop (in Rockford and Peoria) was held to introduce engineers, area contractors, coal ash producers, ready-mixed concrete suppliers, designers, local and state government personnel, and other potential users to the benefits of CLSM flowable slurry. Appropriate handouts were developed and distributed at these seminars. Handouts included information on materials, manufacturing and construction technology found technically and economically acceptable, mixture proportioning parameters, manufacturing methods, technical data, field tests, and evaluation of results, etc.

In order to meet the project objectives and goals for production implementation and market development of CLSM with high-volume Illinois coal ash, activities were divided into separate tasks. These tasks consisted of prototype field production, manufacturing and construction demonstration projects, and technology implementation activities. Task I activities included testing of Illinois coal ash characteristics for use in CLSM. Illinois coal ash producer was selected based upon past cooperative projects. The producer is located in Pekin, IL. In Task II, mixtures for CLSM prototype-scale production in Rockford and Peoria were developed and tested for physical, mechanical, and chemical characteristics. This activity also was the basis for establishing mixture proportions to be used for manufacturing of CLSM for field trials for construction demonstrations. Laboratory mixtures were tested for compressive strength, permeability, shrinkage, setting and hardening, and other properties, as required by IDOT or local construction needs. All testing was conducted in accordance with IDOT, ASTM, ACI, US-EPA, or other similar standards. CLSM produced was field tested at manufacturing and construction sites in Illinois. CLSM mixtures were evaluated and selected for use in the construction demonstrations in Task III. Task IV consisted of two construction demonstrations and technology transfer seminars on the production and use of CLSM slurry containing Illinois coal ash. These seminars were held to inform users of the results of this project and to promote marketability of the CLSM. The seminars were held in Rockford and Peoria, IL. These two geographic regions were selected to expose the largest potential group of engineers, manufacturers, materials specifiers, etc., in the production and use of CLSM. The seminars consisted of a one-day workshop explaining the manufacture and use of CLSM made with Illinois coal ash. Task V consists of monthly progress reports as well as a final report of the project activities.

INTRODUCTION AND BACKGROUND

Introduction

Approximately 5.5 million tons of coal combustion products are generated each year from combustion of Illinois coal. About 3.0 million tons of these coal combustion products are produced in Illinois and the remaining 2.5 million tons are generated in other states (including Wisconsin) burning Illinois coal. The overall utilization rate in the USA for all coal ashes was approximately 30% in 1999 (i.e., about 30 million tons). Illinois coal, when it is burned in conventional boilers, produces Class F, low-lime, fly ash. In general, utilization rate of Class F fly ash in U.S.A. is substantially lower relative to Class C, high-lime, fly ash. This is partly due to the perceived lower quality of Class F fly ash compared to Class C, and greater variation in its properties, especially for Class F fly ash generated from older power plants. Also, there is a significant lack of commercial products that use high-volumes of Class F fly ash; and, there is even a greater lack of use for clean coal ash (scrubber sludge). Due to shrinking landfill space, to solve environmental concerns, and due to increased public awareness and debate, it has become mandatory to find practical solutions to this "ash problem".

Literature Review

A great deal of research work has been reported concerning utilizations of conventional coal combustion by-products [1-16][1]. In 1998, Naik and Singh [16] summarized various applications of fly ash generated from conventional and clean coal technologies. Uses of coal combustion by-products can be categorized into three classes: high-volume applications; medium-volume applications; and low-volume applications. A typical and very successful high-volume application of coal ash is in controlled low-strength materials (CLSM). Class F and C coal fly ash has been used for CLSM [17-24].

Naik et al. reported to ACI in 1989 (later published by ACI in 1990) work done in Milwaukee area for about the last 20 years [17]. CLSM can be defined as a cementitious material which is in a flowable state, easy to place, and has a specified compressive strength of 1,500 psi or less at 28 days [17]. It is used for low-strength, primarily non-structural, applications. In accordance with Naik et. al, in most cases, its desired strength is similar to the surrounding soil. The main uses of this material are for backfilling trenches containing ducts, pipes, etc., around manholes and similar excavations in streets, or backfilling of foundation excavations. It has also been used to backfill mine excavations, abandoned tunnels, sewers, and other underground facilities. In the last five years or so, the use of CLSM is increasing for construction of roadways, highways, and airfield pavements. Naik et. al [17-24] have discussed results of tests performed on Class F and C fly ash CLSM. Based on these results it was concluded that a cement content of about 75 (±25) lb/yd^3 is necessary to produce compressive strength between 50 and 150 psi at the age of 28 days. The flowability of CLSM slurry can be varied by increasing the amount of water added. Naik, et. al [18-21] also developed mixture proportions for low-strength concrete slurry as a controlled low-strength material (CLSM) incorporating ASTM Class F and C fly ash. Compressive strength of these mixtures was varied from

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[1] See corresponding reference number in Appendix A: List of References.

500 psi to 1500 psi with both high and low slump. They concluded that the mixtures developed for their projects could be used as the basis for selecting mixture proportions of both low and high slump flowable fly ash slurry when these materials are utilized.

In 1991, Naik, et. al [20,21] reported on two different ash materials, ASTM Class F and Class C fly ash, as the primary material in developing flowable CLSM slurry mixture proportions. Based on the information obtained as part of their study, it was concluded that a high-volume fly ash CLSM could be produced with either ASTM Class F or Class C fly ash. An additional study on CLSM incorporating Class F fly ash was conducted by Naik, et. al [21]. The CLSM was found to perform well and it was concluded that a high-volume ASTM Class F fly ash CLSM could be successfully produced and used in the construction industry. Ramme, Naik, and Kolbeck [22] studied the application of high-volume fly ash CLSM for backfilling trenches and filling underground facilities. The objective of the study was to expand the utilization of fly ash produced by Wisconsin Electric Power Co. Initially a laboratory and later a field study was conducted using CLSM. CLSM was evaluated for physical, mechanical, and chemical properties, electrical resistivity, polyethylene plastics compatibility, etc. The results indicated that the CLSM could be successfully utilized as a backfill material for trenches. Corrosion potential and the effect on polyethylene pipes were found to be within normally accepted limits. CLSM was also recommended for backfilling around underground power lines where high thermal conductivity, high density, and low porosity of the CLSM material is especially desirable.

Naik and Singh [23] in 1992-1994 studied the effects of incorporating fly ash as well as used foundry sand (used molding sand for castings) in CLSM. Leaching of the CLSM materials was evaluated along with other physical, mechanical, and chemical properties. Leaching analysis of CLSM made with one of the sources of fly ash was found to meet drinking water standards. The chemical composition of the leachate was dependent on the source of the coal ash. Adebayo [24] in 1994, under the supervision of Naik, studied the use of coal ash and used foundry sand in CLSM. An extensive laboratory evaluation of the CLSM material was conducted which included compressive strength, permeability, shrinkage, chemical composition, settlement, setting and hardening, and chemical leachate analysis. He found that foundry sand could be used in conjunction with fly ash to make CLSM. Currently used foundry sand and/or coal fly ash are being specified for construction projects in Wisconsin.

Krell [25] discussed using fly ash CLSM as a backfill in flowing water in Michigan, at a depth of about 20 feet. Class F fly ash CLSM was placed at a relatively stiff consistency (slump of about 6 inches). The mixture contained: 1800 lbs of dry fly Class F ash; 90 lbs of portland cement; and about 670 lbs. of water per cu. yd. of CLSM. It was reported that this material was easily placed under water. He also observed that this material can support the weight of a loaded truck after 24 hours. Krell also performed tests for unconfined compressive strength for the CLSM containing cement, Class F fly ash, and water. He obtained a value of about 100 psi. This was better than any other conventional material for backfilling operations. The modulus of rupture for this material was found to be almost equal to its compressive strength. The CLSM material was also tested for erosion. At present there is no standard test method for erosion of CLSM. Therefore, the material was placed in a tank in which water was continuously poured over it. The aim was to study how much material would be eroded and how it will affect the water quality. Krell showed that CLSM performed better than any other conventional material. Only clean rock fill would be better than the ash CLSM in this respect. Larsen [26] discussed various instances where the CLSM material was successfully used. Iowa-DOT filled two-200 gal. and one-1000 gal. abandoned fuel tanks with flowable fly ash CLSM. This project was completed for $1,140. Removing the tanks was estimated to cost $8,000. In accordance with Federal and State rules, filling in-place tanks with inert solid material is an alternative to tank removal. For Illinois this remains a significant market for CLSM. Several counties in Iowa placed culverts on CLSM bedding [26]. This prevented water from getting to the bottom of the culvert pipe and/or the bedding, and eroding the pipe support. Excavations necessary for placing pipe lines were made smaller when flowable fly ash CLSM was to be used as a backfill, because it is self compacting. CLSM was also used for erosion prevention. A V-shaped drainage ditch for a parking lot in Iowa was lined with riprap (stones, blocks, concrete, or other protective covering material to prevent erosion and scour by water flow) and loose rock. But due to high volume of storm water run off, the material in the riprap was washed away. When this was rebuilt, the ditch was relined with riprap. Then fly ash CLSM slurry was placed through the riprap and in the offset parking area to a depth of 4 inches. The CLSM was also placed over the riprap as a capping material. The overall performance of the CLSM was considered very satisfactory and cost-effective. Voids were created under a bridge pier in St. Paul, Minnesota, and erosion was caused by wash outs. A four-inch pipe was positioned down each pier to the bottom of the bridge pier footing. Riprap was placed into the void around the pipe. Flowable fly ash CLSM slurry was then pumped into the void and through the riprap until it came out into the current. Subsequent sounding test showed that the support for these footings remained very solid.

Edil et. al [27] studied the feasibility of using pozzolanic fly ash (in the presence of moisture reacts with calcium hydroxide and alkalis in cement to form cementitious compounds), either by itself or mixed with sand, as a construction material for waste containment liners and impermeable covers. They noted that the liners can be constructed from pozzolanic ash with or without sand mixtures to meet the usual requirement for the permeability of 10^{-7} cm/s or less for liners. They also investigated the effects of long-term permeation of inorganic leachates solutions on performance of such liner materials. Comparing of leachate from specimens with two different permeabilities showed that calcium and sulfur concentrations were lower when permeability was lower. Sodium, chloride, boron, cadmium, and pH data showed no significant changes and zinc concentrations were higher with lower permeabilities. It was, therefore, concluded that to have a low permeability coal ash liner material, with low level of leachates, major variables were compaction effort and moisture content affecting the permeability of the fly ash liner material and the type and percentage of fly ash used.

In the last three years, Naik et. al [28-35] has continued to demonstrate the feasibility of using by-product materials in CLSM. CLSM has been developed using fluidized bed boiler ash [28], used foundry sand [29, 30], excavated soil [33], wood ash [34], and high-carbon ash [35]. These CLSM materials developed meet performance requirements such as excavatability, cohesiveness, permeability, and environmental considerations. A very important conclusion of these reported projects [36-43] was that coal ash was necessary in CLSM when other recyclable materials were used. State-of-the-art reports presented by Naik and Ramme [31, 32] emphasize the use of coal ash and other by-products not meeting ASTM C 618 standards in CLSM applications.

IDOT CLSM Mixture Requirements

The Illinois Department of Transportation (IDOT) specifies three different standard mixture proportions for CLSM: Mixture 1 contains 50 lb/yd^3 of cement, 125 lb/yd^3 fly ash, 2900 lb/yd^3 fine aggregate, and 50 to 65 gal./yd^3 of water; Mixture 2 contains no fly ash, but has 125 lb/yd^3 of cement, 2500 lb/yd^3 of fine aggregate, 35 to 50 gal/yd^3 of water and air entrained to contain between 15 and 25% air content. Mixture 3 contains 40 lb/yd^3 of cement, 125 lb/yd^3 of fly ash, 2500 lb/yd^3 of fine aggregate, and is also air entrained to contain 15 to 25% air content. Alternate mixture proportions are also allowed to be submitted to IDOT provided that they meet the following mixture performance criteria: flow greater or equal to seven inches, air content between 0 and 25%, dynamic cone penetrometer at three day age less than 1.5 inches, and compressive strength at 28 and 180 days greater than 30 psi and less than 125 psi. Alternate mixture designs submitted to IDOT must also specify the source of all materials; gradation of fine aggregate; volumes, specific gravity, unit weights, etc. used to establish mixture proportions; type and dosage of admixtures; flow and air content; and compressive strength at 28 and 180 days. These specifications are applicable to projects funded by IDOT, but other CLSM performance requirements may be specified depending on the specific application.

EXPERIMENTAL PROCEDURES

Materials

Type I portland cement (ASTM C 150) was used in this work. An ASTM Class F fly ash from Illinois from a wet collection process was also used for the current study. The as-received moisture content of Class F fly ash ranged between 10 and 20 percent. Two types of fine aggregate were used for this project. One was a natural sand from (Peoria, IL) with a 1/4-in. (6.35) mm nominal maximum size, while the second type was a fine crushed sand obtained from a quarry located in Rockford, IL.

Material Characterization

Materials used for producing flowable slurry (CLSM) used for this project were tested in accordance with standard ASTM test methods. ASTM test procedures for fly ash and cement are given in Reference 36. ASTM test procedures for fine aggregate are given in Reference 37. The Illinois coal fly ash (requirements per ASTM C 618) was characterized for chemical properties including oxides, elements, mineralogy, and the following physical tests: fineness (ASTM C 430), strength activity index with cement (ASTM C 109), water requirement (ASTM C 109), autoclave expansion (ASTM C 151), and specific gravity (ASTM C 188). Fine aggregates were tested per ASTM C 33 requirements for the following physical properties: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 128), fineness (ASTM C 136), and material finer than #200 sieve (ASTM C 117).

Manufacturing of Laboratory Mixtures

Prior to prototype manufacturing, laboratory mixtures were prepared to establish preliminary mixture proportions and to determine performance of the mixtures prior to introducing the manufacturer to CLSM manufacturing technology. Similar laboratory mixture procedures were followed to those outlined in ACI 229R for mixing CLSM in a ready-mixed concrete truck mixer. First, approximately 70 to 80 percent of the water required was added to the mixer. Subsequently, approximately half of the fine aggregate was added to the mixer, mixed for one minute, then all of the cement and half of the ash was added to the mixer, again mixed for one minute, then the remaining ash was added. Finally, with continued mixing, the remaining fine aggregate with the remaining water was added. If during the mixing process, the mixture appeared to be dry, more water was added. After all materials were added, the mixture was mixed for minimum three minutes.

Manufacturing of CLSM Mixtures for Prototype-Scale Production and Manufacturing Demonstration

All ingredients were batched and mixed at the ready-mixed concrete plant of Meyer Material Company, Rockford, or at United Ready-Mix, Inc., Peoria. All CLSM was manufactured in accordance with the recommendations of ACI 229R. At Meyer Material Company, fine crushed sand, cement, and water were automatically batched and added into a conventional ready-mixed concrete truck mixer. Ash was weighed separately for each ready-mixed truckload via a portable hopper typically used for portable batch plant facilities. At the facilities of United Ready-Mix, sand, cement, and water were also automatically batched into a central mixer. Ash was loaded directly into a hopper with a front-end loader and then transported to the central mixer by a belt conveyor. In order to prevent fly ash from bridging within the hopper, ash was slowly added into the bin while the bin was kept open to the conveyer. Only the amount of ash required for each mixture was added into the bin.

For prototype mixtures, CLSM was transported to the facilities of Rockford Sand and Gravel, Inc., Rockford, IL, or to the facility of the URMI in Peoria, IL for fresh CLSM testing and casting of test specimens. Additional water was added in the mixture as needed for achieving the desired level of workability (flow). Whenever any additional water was added, the CLSM mixture was mixed at a high mixing speed for an additional minimum three minutes.

Testing and Specimen Preparation

Fresh CLSM properties such as air content (ASTM D 6023), flow (ASTM D 6103), unit weight (ASTM D 6023), and temperature (ASTM C 1064) were measured and recorded. Air temperature was also measured and recorded. Standard ASTM test procedures for fresh CLSM properties were followed for these tests [37]. The amount of bleedwater and the level of the solids (settlement) in the 6x12-inch cylinders were also recorded.

Test specimens were prepared for each CLSM mixture for compressive strength and permeability testing. All test specimens were cast in accordance with ASTM D 4832. These specimens were typically initially cured for three to seven days in their molds at about 75° ± 10 °F at the location of the specimen preparations at the manufacturing facilities in Rockford and Peoria, IL. They were then brought to the lab for further testing. For continued curing, these specimens were removed from the molds and placed in a standard moist-curing room, maintained at 100% R.H. and 74 ± 3° F, starting at the age of approximately seven days.

Setting and hardening of CLSM was measured following the State of Illinois Department of Transportation (IDOT) specifications. IDOT specifies the use of a dynamic cone penetrometer (DCP) following Illinois Test Procedure 401. The DCP consists of a 17.6 lb hammer dropped 22.6 inches, which drives a conical end into the CLSM. The total number of blows are recorded for each 6-inch depth. This is then converted to an equivalent number of blows per inch. For laboratory mixtures, the DCP test was evaluated for 6x12-inch CLSM cylinders which were kept in the mold during the test to simulate confining pressure from surrounding CLSM that might be placed at a construction site.

Properties of hardened CLSM mixtures were evaluated as a function of age. Compressive strength (ASTM D 4832) and water permeability tests (ASTM D 5080) using the falling head, constant tailwater pressure method, were conducted.

RESULTS AND DISCUSSION

The results of this project are presented corresponding to each project task: Task I: Material Selection/Characterization for CLSM Mixtures, Task II, CLSM Mixtures for Prototype-Scale Production and Testing, Task III: Selection of Mixtures for Construction, and Task IV: Demonstration/Technology Transfer.

Task I: Material Selection/Characterization for CLSM Mixtures

Materials utilized for manufacturing CLSM slurry were tested and evaluated for its physical, mechanical, and chemical characteristics. Testing work was carried out using standard ASTM, ACI, or US-EPA test methods as required. Characteristics evaluated of the wet collected Class F ash (WF) included: gradation, strength development with cement, oxides, and mineralogy, Tables 1 to 6. These properties were used in determining mixture proportions developed for this project. Fine crushed sand (FCS) was used for the Rockford mixtures as a source of fine aggregate for the CLSM met ASTM C 33 requirements with the exception of the material passing No. 100 sieve, Table 1. This finer material, although not normally used in structural concrete, would be beneficial when used in CLSM. The finer materials assist the flow characteristics of the material. The ash used for the project, a wet collected Class F fly ash (WF), was also characterized per ASTM C 618 requirements. The ash met ASTM requirements for

Class F fly ash with the exception of loss on ignition, and the sum of (SiO_2 + Al_2O_3 + Fe_2O_3).

Table 1: Sieve Analysis (ASTM C 136)

Sieve Analysis				
Sieve Size	% Passing*			ASTM C 33 % Passing for Sand
	Sand (Lab Mixtures)	Sand (Field Mixtures)	FCS (Fine Crushed Sand)	
3/8" (9.5 mm)	100	100	100	100
#4 (4.75 mm)	99.9	99.7	99.7	95 to 100
#8 (2.36 mm)	88.6	--	84.6	80 to 100
#16 (1.18 mm)	69.9	67.7	55.0	50 to 85
#30 (600 µm**)	49.1	--	33.9	25 to 60
#50 (300 µm**)	17.7	15.3	24.0	10 to 30
#100 (150 µm**)	3.0	4.7	16.9	2 to 10

Table 2: Unit Weight and Voids (ASTM C 29)

Source	Unit Weight (lbs/ft^3)	Voids (%)
FCS	88.9	
Fine Aggregate (Laboratory Mixtures)	110.4	38.0

Table 3: Specific Gravity of Fly Ash (ASTM C 311/C 188)

Fly Ash Source	Specific Gravity	
	Actual	Average
WF	2.46	2.45
	2.46	
	2.41	

Table 4: Specific Gravity (ASTM C 128)

Fine Aggregate Source	Bulk Specific Gravity	Bulk Specific Gravity (SSD Basis)	Apparent Specific Gravity
Fine Aggregate (Laboratory Mixtures)	2.64	2.67	2.72
Fine Crushed Sand (Laboratory and Field Mixtures)	2.74	2.78	2.74

Table 5: Chemical Analysis

Analysis Parameter	Material		ASTM C 618 Requirements		
	FCS	WF	Class N	Class C	Class F
Silicon Dioxide, SiO_2	3.9	26.6	--	--	--
Aluminum Oxide, Al_2O_3	1.5	12.0	--	--	--
Iron Oxide, Fe_2O_3	0.8	18.5	--	--	--
SiO_2 + Al_2O_3 + Fe_2O_3	6.2	57.1	70.0, Min.	50.0, Min.	70.0, Min.
Calcium Oxide, CaO	31.3	5.6	--	--	--
Magnesium Oxide, MgO	22.3	1.2	--	--	--
Titanium Oxide, TiO_2	0.0	0.5	--	--	--
Potassium Oxide, K_2O	0.6	1.1	--	--	--
Sodium Oxide, Na_2O	0.0	0.6	--	--	--
Sulfate, SO_3	0.0	1.0	4.0, Max.	5.0, Max.	5.0, Max.
Loss on Ignition, LOI (@ 750 C)	42.7	34.1	10.0, Max.*	6.0, Max.*	6.0, Max.*
Moisture Content	0.0	1.6	3.0, Max.	3.0, Max.	3.0, Max.
Available Alkali, Na_2O Equivalent (ASTM C-311)	NA	1.1	1.5, Max.**	1.5, Max.**	1.5, Max.**

* Under certain circumstances, up to 12.0% max. LOI may be allowed.
** Optional. Required for ASR Minimization.

Table 6: Mineralogy

MINERALOGY (% by Weight)		
Analysis Parameter	FCS	WF
Amorphous	--	74.4
Dolomite, $CaMg(CO_3)_2$	98.0	--
Hematite, Fe_2O_3	--	4.0
Magnetite, Fe_3O_4	--	4.7
Mullite, $Al_2O_3.SiO_2$	--	7.0
Quartz, SiO_2	2.0	3.9

In order to establish performance characteristics of CLSM prior to prototype-scale production, laboratory mixtures were produced. Two separate series of mixtures, Series 1 (Rockford mixtures) which used fine crushed sand (FCS) as the fine aggregate, and Series 2 (Peoria mixtures), which used standard concrete sand as the fine aggregate. Series 1 laboratory mixtures consisted of two groups of mixtures: Series 1A, which established preliminary performance data, and Series 1B, which had more extensive testing.

A total of six mixtures were produced for Series 1A mixtures (Table 7). Fly ash content of the mixtures, expressed as a percentage of total fines (fly ash and crushed fine sand), varied from 100% (Mixture S1), to 0% (Mixture S6). Intermediate fly ash concentrations were established at 80%, 50%, 40%, and 27% for Mixtures S2, S3, S4, and S5, respectively. Cement content of the mixtures varied from 100 lb/yd^3 for Mixture S1, to 51 lb/yd^3 for Mixture S4. To obtain the same workability (flow), water content of the mixtures was reduced as the percentage of fly ash decreased. Compressive strength of all mixtures were tested at the age of 7, 28 and 182 days (Table 8). All mixtures exhibited satisfactory levels of compressive strength (less than 100 psi at age of 28 days). Mixtures with lowest cement content produced the lowest strength. After evaluating these results, it was determined that the expanded laboratory mixture series containing fine crushed sand should contain a consistent cement content of approximately 95 lb/yd^3.

Based upon the results of Series 1A, five Series 1B mixtures were produced (Table 9). Similar to the Series 1A ash mixtures, ash content of the mixtures varied from 100% (Mixture A1) to 0% (Mixture A5). Target values for ash content of the remaining mixtures were 67% for Mixture A2, 50% for Mixture A3, and 33% for Mixture A4. Flow of the mixtures was maintained at about ten inches. Water requirement of the mixtures decreased with increased fine crushed sand content, 919 lb/yd^3 of water for Mixture A1 (100% ash) to 598 lb/yd^3 for Mixture A5 (0% ash). As expected, density of the CLSM also increased as the amount of fine crushed sand increased: 90 lb/ft^3 to 134 lb/ft^3 for mixtures A1 to A5, respectively. Initially, at the age of 3 days, compressive strength of mixtures varied between 20 to 35 psi. Compressive strength of the mixtures were evaluated at the ages of 3, 7, 28, 56, and 91 days (Table 10). Compressive strength of the mixtures generally increased with age.

Dynamic cone penetrometer (DCP) values (Fig. 1), for all mixtures were one inch/blow or less at the age of 24 hours. IDOT CLSM specifications indicate that 1.5-in/blow or less as adequate to support construction loading. Settlement (measured level of solids) of the mixtures (Fig. 2) reveal that increasing fine crushed sand content combined with reduced fly ash content generally increased the settlement of the mixtures. Settlement of Mixture A5 without ash was 0.25 inch per foot height of CLSM mixture. Settlement of the mixtures improved significantly with 35% ash content (Mixture A4) to less than 0.15 in/ft.

Water permeability of all Series 1A laboratory mixtures were very low, 2.9 x 10^{-6} cm/sec to 43 x 10^{-6} cm/sec (Table 11). At the age of 132 days, impermeability increased. The decrease in permeability is due to decreased void structure within the CLSM due to hydration of cement and/or pozzolonic reaction of the Illinois coal fly ash used.

Table 7: CLSM Laboratory Mixture Proportions – Series 1A

Mixture Number	S1	S2	S3	S4	S5	S6
Lab Mixture No.	I4	I9	I6	I7	I8	I5
Fly Ash Content, A/(A+R), (%)	100	80	50	40	27	0
Fine Crushed Sand Content, R/(A+R), (%)	0	20	50	60	73	100
Cement, (lb/yd^3), C	100	70	76	51	79	80
Fly Ash, Dry Wt., A, (lb/yd^3), A	1335	1215	1000	830	649	0
Fine Aggregate, Dry Wt., (lb/yd^3), R	0	300	1015	1250	1720	2895
Water, W (lb/yd^3)	915	890	765	760	630	625
Flow (in)	10	10	10	10	9-3/4	10
Air Content (%)	5.6	4.6	2.9	4.6	2.4	0.4
Air Temperature (°F)	71	73	70	67	68	70
CLSM Temperature (°F)	69	71	65	69	69	64
Fresh CLSM Density (lb/ft^3)	87.0	91.7	105.6	106.8	113.9	133.3

Table 8: CLSM Compressive Strength of Laboratory CLSM Mixtures – Series 1A

Mixture Number	Fly Ash Content, %	Fine Crushed Sand Content, %	Compressive Strength, psi					
			Test Age					
			7-days		28-days		182-day	
			Act.	Ave	Act.	Ave	Act.	Ave.
S1	100	0	25	30	50	50	--	--
			30		50		--	
			30		50		--	
S2	80	20	10	15	20	20	40	35
			15		25		35	
			15		20		35	
S3	50	50	30	30	45	35	85	75
			30		35		70	
			30		30		65	
S4	40	60	20	20	30	25	45	45
			15		30		55	
			20		20		40	
S5	27	73	40	30	65	70	90	100
			30		70		115	
			25		75		--	

S6	0	100	30	30	50	45	45	45
			35		40		40	
			30		45		50	

Table 9: CLSM Laboratory Mixture Proportions – Series 1B

Mixture No.	A1	A2	A3	A4	A5
Fly Ash Content, A/(A+R), (%)	100	67	53	35	0
Fine Crushed Sand Content, R/(A+R), (%)	0	33	47	65	100
Cement, (lb/yd^3), C	97	92	94	90	97
Fly Ash, Dry Wt., A, (lb/yd^3), A	1425	1140	1025	740	0
Fine Aggregate, Dry Wt., (lb/yd^3), R	0	560	905	1365	2935
Water, W (lb/yd^3)	919	860	766	723	598
Flow (in)	10 ¼	10	10 ½	10 ½	10
Air Content (%)	3.6	4.0	3.4	2.3	1.4
Air Temperature (°F)	73	75	73	75	72
Slurry Temperature (°F)	67	74	66	73	68
Density of Fresh Slurry (lb/ft^3)	90.4	98.2	103.4	108.2	134.4
Yield (ft^3)	5.7	6.0	5.9	6.1	5.7

Table 10: CLSM Compressive Strength of Laboratory CLSM Mixtures – Series 1B

Mixture Number	Fly Ash Content, %	FCS Content, %	Compressive Strength, psi									
			Test Age									
			3-days		7-days		28-days		56-days		91-days	
			Act.	Ave	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
A1	100	0	20	20	35	25	50	50	55	55	55	65
			20		30		50		55		70	
			20		15		50		50		70	
A2	67	33	20	25	45	40	65	65	80	80	85	85
			25		35		65		70		90	
			25		35		70		85		75	
A3	53	47	35	30	40	40	75	75	95	95	110	110
			30		45		75		100		115	
			30		35		70		95		105	
A4	35	65	20	20	35	30	65	60	60	60	70	70
			20		30		55		55		65	
			20		30		65		70		70	
A5	0	100	30	35	40	40	50	65	40	40	50	50
			35		40		75		45		45	
			35		45		65		35		50	

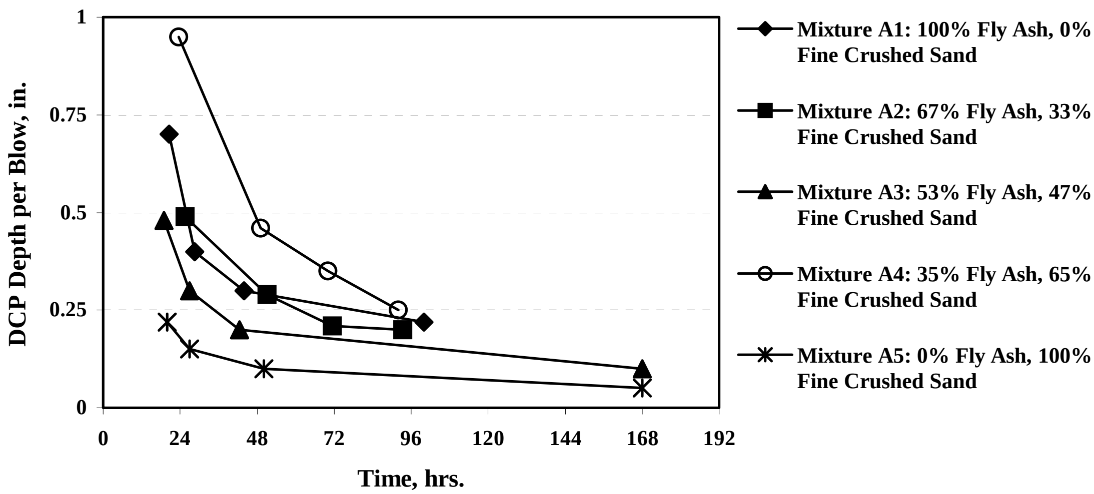

Fig. 1 - Setting of Series 1B CLSM Laboratory Mixtures

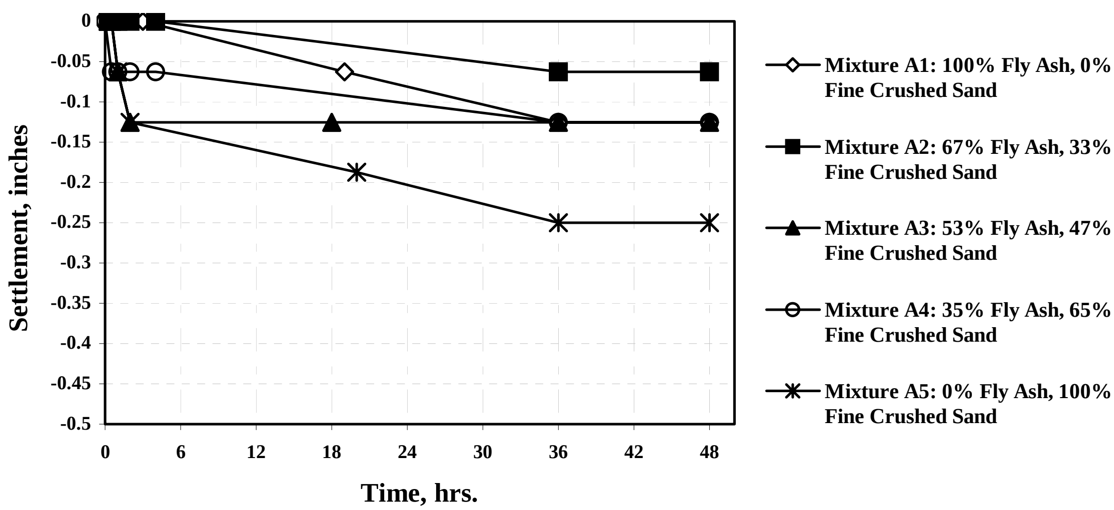

Fig. 2 - Settlement of Series 1B CLSM Laboratory Mixtures

Table 11: Water Permeability of Series 1B Laboratory Mixtures

Mixture Number	Fly Ash Content, %	FCS Content, %	Permeability (cm/sec)	
			67-day age	132-day age
A1	100	0	10.6×10^{-6}	7.2×10^{-6}
A2	67	33	43.0×10^{-6}	41.4×10^{-6}
A3	53	47	2.86×10^{-6}	2.51×10^{-6}
A4	35	65	7.36×10^{-6}	5.88×10^{-6}
A5	0	100	34.0×10^{-6}	27.2×10^{-6}

The second series of laboratory CLSM mixtures, Series 2 Peoria mixtures, consisted of mixtures using standard concrete sand in combination with Illinois coal ash (Table 12). Similar to Series 1 mixtures, the ash content of the mixtures varied from 100% to 0% (ash content expressed as a percentage of total fines; i.e., ash and fine aggregate). A total of five new mixtures were produced for Series 2. Mixture L1, 100% Illinois coal ash, was taken as the same mixture from Series 1, Mixture A1. The amount of fly ash used for mixtures L1 to L6 was 100%, 81%, 60%, 40%, 20%, and 4%, respectively. The fly ash used for Mixture L6, 4% Class C fly ash, met ASTM C 618 requirements. Mixture L6 was produced with the IDOT CLSM mixture proportions to provide a benchmark for performance between the standard IDOT mixture with mixtures produced with Illinois Class F coal ash.

In order to provide a transition between the 100% ash mixture, Mixture L1 and the IDOT standard mixture (Mixture L6) cement was reduced as the amount of sand in the mixture was increased. Flow of the mixtures varied between 10-¼ to 11-½ inches. Water requirement to maintain this range of flow decreased as the amount of Illinois coal ash in the mixture decreased and the amount of the sand increased. As expected, unit weight of the mixtures increased as he amount of sand increased. Unit weight of Mixture L1 (0% sand) was 90 lb/ft3, while Mixture L6 (96% sand) increased to 132 lb/ft^3. Setting characteristics of Series 2 mixtures are shown in Fig. 3.

All Series 2 CLSM mixtures reflected satisfactory setting characteristics within 36 hours (DCP depth per blow of 1.5 in or less). Mixture L1 (100% fly ash), L2 (81 % fly ash), L3 (60 % fly ash), and L5 (20 % fly ash) achieved a DCP value of 1.5 inches or less at 24 hours or less. The mixture with 100% fly ash, L1, exhibited the fastest setting time compared with other mixtures, including the IDOT Mixture L6. Settlement measurements of Series 2 mixtures are shown in Fig 4. Settlement of mixture for standard IDOT Mixture L6, with 96% sand and 4% Class C ash, had a very high settlement, 0.75 in/ft. It is believed that this was due to the lack of fines in the mixture. The settlement values also correspond to the amount of bleedwater in the mixture.

Compressive strength of the mixtures were tested at the ages of 3, 7, 28, 56 and 91 days (Table 13). All mixtures obtained satisfactory compressive strength levels for CLSM applications when the material may have to be excavated in the future (less than 100 psi). Mixtures L5 and L6 achieved the lowest strength, 15 psi or less at 56 and 91 days. Although low, a 10 psi unconfined compressive strength is equivalent to 1,440 lb/ft^2 for soil backfill. Typically this level of strength is acceptable for many backfill applications. Water permeability of the Peoria mixtures (Series 2) were slightly higher (less impermeable) than Series 1 mixtures (Table 14).

Table 12: Laboratory Mixtures for Series 2 CLSM

Mixture Number	L1	L2	L3	L4	L5	L6
Lab Mixture Number	A1	B1	B3	B2	B4	B5
Fly Ash Content, %	100	81	60	40	20	4
Sand Content, %	0	19	40	60	80	96
Fly Ash Type	WF	WF	WF	WF	WF	Class C
Cement, (lb/yd^3)	97	92	85	82	40	25
Fly Ash, (lb/yd^3)	1425	1175	1180	900	547	127
SSD Fine Aggregate, (lb/yd^3)	0	280	785	1325	2185	2840
Water, (lb/yd^3)	919	958	685	700	524	570
Flow, (in.)	10-1/4	10-1/2	10-1/2	11	11	11-1/2
Air Content, (%)	3.6	3.7	3.4	1.8	1.8	0.3
Air Temperature, (°F)	73	75	73	73	78	79
Fresh CLSM Temperature, (°F)	67	73	71	74	74	75
Unit Weight, (lb/yd^3)	90.4	92.8	101.4	111.2	122.1	132.0

Table 13: CLSM Compressive Strength of Laboratory CLSM Mixtures – Series 2

Mixture Number	Fly Ash Content, %	Sand Content, %	Compressive Strength, psi									
			Test Age									
			3-days		7-days		28-days		56-days		91-days	
			Act.	Ave	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
L1	100	0	20	20	35	25	50	50	55	55	55	65
			20		30		50		55		70	
			20		15		50		50		70	
L2	81	19	20	30	30	30	35	35	30	30	40	35
			30		20		35		35		30	
			40		35		35		30		30	
L3	60	40	10	15	25	25	45	45	50	55	40	45
			20		25		50		55		45	
			10		20		45		55		50	
L4	40	60	65	45	30	30	45	40	65	60	60	60
			35		25		40		65		60	
			30		35		35		55		60	
L5	20	80	15	15	10	10	25	30	20	15	5	10
			15		10		30		15		10	
			10		15		30		10		10	
L6	4	96	5	5	10	10	10	10	15	15	5	10
			5		10		5		15		15	
			--		10		20		20		5	

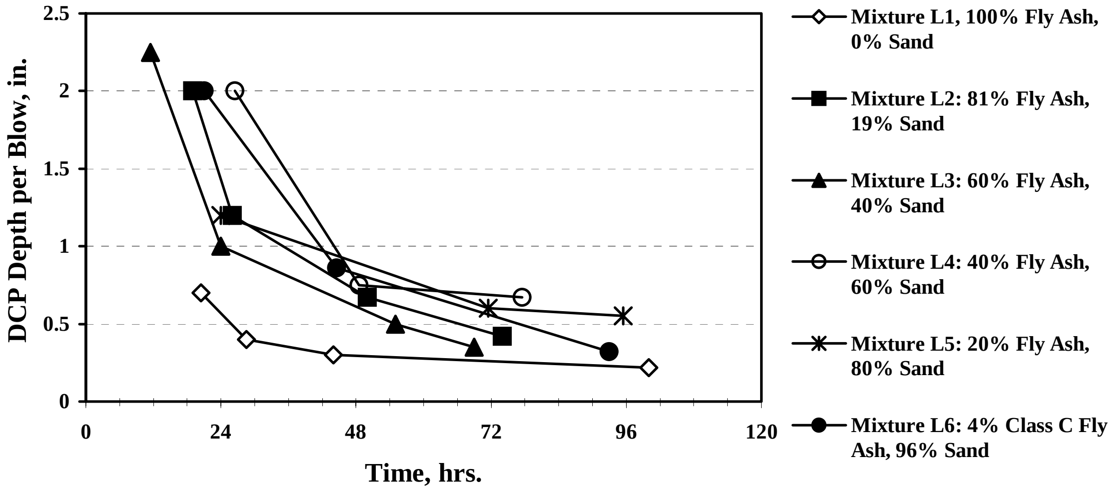

Fig. 3 - Setting of Series 2 CLSM Laboratory Mixtures

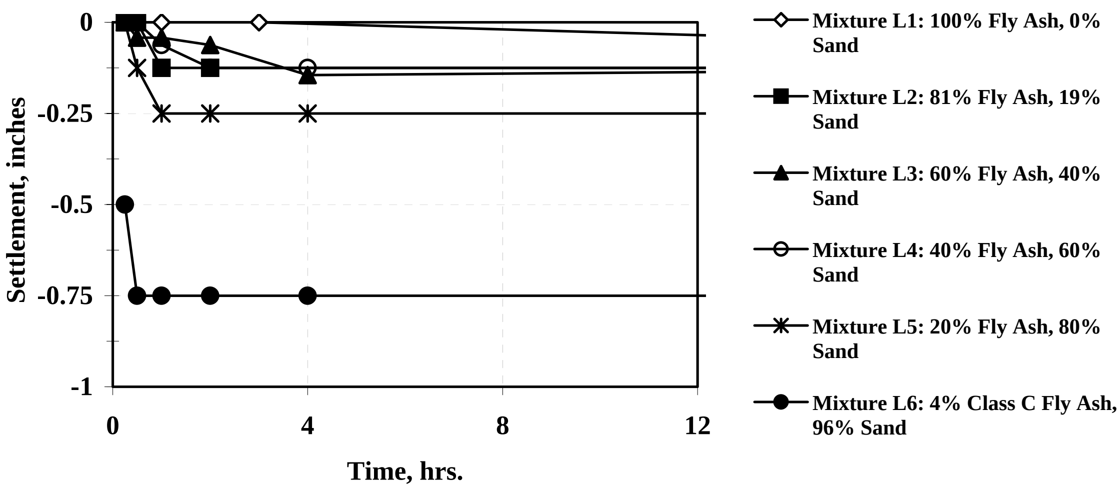

Fig. 4 - Settlement of Series 2 CLSM Laboratory Mixtures

Table 14: Water Permeability of Series 2 Laboratory Mixtures

Mixture Number	Fly Ash Content, %	Sand Content, %	Permeability (cm/sec)	
			56-day age	91-day age
L1	100	0	10.6×10^{-6}	7.2×10^{-6}
L2	81	19	60.5×10^{-6}	54.5×10^{-6}
L3	60	40	110×10^{-6}	66.0×10^{-6}
L4	40	60	154×10^{-6}	125×10^{-6}
L5	20	80	228.7×10^{-6}	84.6×10^{-6}
L6	4	96	45.1×10^{-6}	20.8×10^{-6}

Task II : CLSM Mixtures for Prototype-Scale Production and Testing

Prototype-scale production of CLSM was conducted at the facilities of Meyer Material Company and Rockford Sand and Gravel, Inc. (Series F1), Rockford, IL, and at United Ready-Mix, Inc., Peoria, IL (Series F2). Production at Meyer Material Co. and Rockford Sand and Gravel, Inc., consisted of eight CLSM mixtures using a combination of Illinois coal ash and fine crushed sand as fine aggregate. The purpose of the prototype production at Rockford and Peoria facilities was to familiarize the producers with the handling of Illinois coal ash for CLSM and to obtain test data from these production mixtures. The first series of prototype production mixtures, Series F1, consisted of five mixtures, Mixtures 1 to 5, containing 100%, 64%, 47%, 23%, and 0% fly ash, respectively (Table 15). Mixtures 1, 2, and 3 were mixed with very high flows, 24 inches. Mixture 4, 23% fly ash, had a higher flow than a similar laboratory mixture, 15-1/2 inches versus 10-1/2 inches. Mixture 4 also had approximately 25 lb/yd^3 higher cement content than the laboratory mixtures. Mixture proportions of Mixture 5 was also close to the corresponding laboratory mixture, with the exception of a lower flow and a slightly higher cement content. The lower flow and higher cement content was expected to increase the compressive strength of the mixture. Compressive strength of prototype CLSM Series F1 mixtures were measured at 21, 28, and 160 days (Table 16). Mixtures 1, 2, and 3, which had a very high flow, achieved compressive strength of 25 psi at the age of 28 days, and 45 to 55 psi at the 160-day age. These data would indicate that these CLSM mixtures, when produced at very high flows, would still achieve compressive strength that would be quite satisfactory to support construction loading. Compressive strength of Mixture 4 was very high at the age of 160 days, 205 psi. CLSM with this compressive strength would be difficult to excavate without the use of a backhoe or jackhammer. This CLSM would be suitable for applications where the material would not be expected to be excavated in the future, such as under slabs and roadway pavements. If future excavation is expected, the cement content of the mixture should be reduced. Since several of Series F1 mixtures fell outside of the expected range of laboratory mixtures, three additional prototype-scale mixtures were produced, Series F1A (Table 17).

Series F1A Mixtures 6, 7 and 8 contained 68%, 51%, and 33% fly ash, respectively (Table 17). Approximately three cu.yd. batches were produced for each of these new prototype-scale mixture. Similar to the other CLSM mixtures, unit weight of these mixtures increased as the amount of fine crushed sand increased. Flow of the three Series F1A mixtures were between 10-1/2 and 11-1/2 inches, closer to the flow obtained from the laboratory mixtures. Cement content of the CLSM mixtures was also approximately the same, 97 to 99 lb/yd^3, as equivalent laboratory mixtures. Compressive strength of the Series F1A mixtures was tested at the age of 7, 28, and 160 days. Compressive strength of Mixtures 6 and 7 were approximately the same, 25 to 30 psi at the age of 7 days, 50 psi at 28 days, and 90 to 100 psi at 160 days. Both of these CLSM mixtures can expected to be excavatable. Mixture 8, 33% fly ash and 67% fine crushed sand attained a slightly higher compressive strength compared with Mixtures 6 and 7. Compressive strength was 35 psi at the age of 7 days, 75 psi at 28 days, and 160 psi at 160 days. To achieve an excavatable mixture, the cement content of Mixture 8 should be decreased from 98 lb/yd^3 to approximately 75 lb/yd^3 or less.

Table 15: CLSM Field Mixture Proportions – Series F1

Mixture No.	1	2	3	4	5
Fly Ash Content, A/(A+R), (%)	100	64	47	23	0
Fine Crushed Sand Content, R/(A+R), (%)	0	36	53	77	100
Cement, (lb/yd^3), C	86	86	99	122	106
Fly Ash, Dry Wt., A, (lb/yd^3), A	815	730	700	680	0
Fine Aggregate, Dry Wt., (lb/yd^3), R	0	405	780	1520	3195
Water, W (lb/yd^3)	1245	1055	970	820	535
Flow (in)	24	24	24	15-1/2	6
Fresh CLSM Density (lb/ft^3)	79.7	84.4	94.4	111.8	138.0
Settlement, (in)	1-3/8	¾	1/4	0	0

Table 16: CLSM Compressive Strength of Field CLSM Mixtures – Series F1

Mixture Number	Fly Ash Content, %	Fine Crushed Sand Content, %	Compressive Strength, psi					
			Test Age					
			21-days		28-days		160-day	
			Act.	Ave	Act.	Ave	Act.	Ave.
1	100	0	15	15	20	25	45	45
			15		25		50	
			20		25		40	
2	64	36	20	20	20	25	60	55
			25		25		70	
			20		30		40	
3	47	53	30	35	40	40	95	80
			35		40		65	
			35		35		85	
4	23	77	140	115	120	130	225	205
			105		110		195	
			95		155		195	
5	0	100	90	85	85	95	105	95
			85		100		100	
			85		95		85	

Table 17: CLSM Field Mixture Proportions – Series F1A

Mixture No.	6	7	8
Fly Ash Content, A/(A+R), (%)	68	51	33
Fine Crushed Sand Content, R/(A+R), (%)	32	49	67
Cement, (lb/yd^3), C	99	97	98
Fly Ash, Dry Wt., A, (lb/yd^3), A	1160	975	730
Fine Aggregate, Dry Wt., (lb/yd^3), R	570	960	1440
Water, W (lb/yd^3)	875	800	740
Flow (in)	10- ½	10- ½	11- ½
Density of Fresh Slurry (lb/ft^3)	100.0	104.4	111.2
Yield (yd^3)	2.8	2.8	2.9

Table 18: CLSM Compressive Strength of Field CLSM Mixtures – Series F1A

Mixture Number	Fly Ash Content, %	Fine Crushed Sand Content, %	Compressive Strength, psi					
			Test Age					
			7-days		28-days		160-day	
			Act.	Ave	Act.	Ave	Act.	Ave.
6	68	32	25	25	45	50	100	100
			25		50		120	
			25		55		85	
7	51	49	25	30	45	50	90	90
			30		50		95	
			30		50		80	
8	33	67	35	35	75	75	175	160
			40		75		160	
			35		75		145	

CLSM produced at the facilities of United Ready-Mix, Peoria, IL used coal ash and standard concrete sand as the fine aggregate. These CLSM mixtures, Series F2, consisted of six mixtures, Mixtures F1 to F6, which contained 100%, 83%, 50%, 43%, 20%, and 4% coal ash, respectively (expressed as percentage of total fines in the mixture; i.e., fly ash and standard concrete sand, Table 19). All mixtures used Illinois coal ash with the exception of Mixture F6, which used Class C fly ash. Mixture F6 is a standard IDOT CLSM mixture, but modified per the requirements of the City of Peoria, IL (reduction in the cement content). Flow of the Series F2 mixtures ranged between 10-1/2 and 12-3/4 inches. As expected, unit weight of the CLSM mixtures increased as the percentage of standard concrete sand increased in the mixture. Cement content of the mixtures was decreased as the amount of sand was increased in the mixture from 115 lb/yd^3 for Mixture F1, 100% Illinois coal fly ash, to 60 lb/yd^3 for Mixture F5, 20% Illinois coal fly ash. The reduction in cement content was necessary to provide a transition in compressive strength values to the standard IDOT/City of Peoria mixture, (Mixture F6).

Compressive strength of Series F2 mixtures was measured at the ages of 8, 28, and 100 days (Table 20). Compressive strength of Series F2 CLSM mixtures typically increased as the amount of fly ash was increased in the mixture. A significant increase was obtained at all test ages, particularly at the age of 100 days. Compressive strength of mixtures increased from 50 psi for Mixture F5, 20% Illinois coal fly ash, to over 1000 psi for the 100% Illinois coal fly ash Mixture F1, at the age of 100 days. Compressive strength obtained for Mixture F5, 20% Illinois coal ash, is considered to be in line with results obtained from the laboratory mixtures. Mixture F5 achieved 20 psi at the 8-day age, 40 psi at 28 days, and 50 psi at 100 days. Results of Mixture F6 also meet the compressive strength requirements of the Illinois DOT of less than 125 psi at 180 days and greater than or equal to 35 psi at the age of 28 days.

Task III: Selection of Mixtures for Construction

Task III consisted of review of the results of the laboratory and field production test results and selection of the CLSM slurry mixtures for future construction needs. The CLSM mixtures selected were based upon the prototype manufacturing results obtained at each of the facilities, Series 1 at Meyer Materials Company and Rockford Sand and Gravel Inc., Rockford, IL, and Series 2 for mixtures produced at United Ready-Mix, Inc., Peoria, IL. Final mixture proportions are presented in Conclusions and Recommendations section of this report. Differences in mixture proportions recommended are based on the equipment used at each plant.

Table 19: Field Mixtures for Series F2 CLSM

Mixture Number	F1	F2	F3	F4	F5	F6
Field Mixture Number	P2	P3	P4	P5	P6	P1
Fly Ash Content, %	100	83	50	43	20	4
Sand Content, %	0	17	50	57	80	96
Fly Ash Type	WF	WF	WF	WF	WF	Class C
Cement, (lb/yd^3)	115	104	95	80	60	25
Fly Ash, (lb/yd^3)	1950	1645	1370	1016	574	124
SSD Fine Aggregate, (lb/yd^3)	0	335	1370	1345	2240	2770
Water, (lb/yd^3)	805	685	610	524	517	511
Flow, (in.)	10-1/2	10-1/2	11-3/4	10-3/4	12-3/4	11-1/4
Air Content, (%)	3.6	4.2	3.9	3.7	1.5	3.4
Air Temperature, (°F)	93	93	94	95	94	88
Fresh CLSM Temperature, (°F)	91	89	90	90	93	85
Unit Weight, (lb/yd^3)	106.2	102.7	104.1	110.5	120.4	127.0

Table 20: CLSM Compressive Strength of Field CLSM Mixtures – Series F2

Mixture Number	Fly Ash Content, %	Fine Crushed Sand Content, %	Compressive Strength, psi					
			Test Age					
			8-days		28-days		100-day	
			Act.	Ave	Act.	Ave	Act.	Ave.
F1	100	0	200	205	530	565	1095	1075
			210		595		995	
			200		570		1130	
F2	83	17	135	125	375	365	555	485
			120		355		395	
			120		365		505	
F3	50	50	55	60	125	130	180	180
			55		140		180	
			65		125		185	
F4	43	57	50	50	110	110	165	170
			50		115		170	
			55		105		170	
F5	20	80	20	20	40	40	45	50
			20		35		55	
			20		40		55	
F6	4	96	20	20	35	35	50	40
			20		30		35	
			20		35		40	

Task IV: Field Activities & Construction Specifications for Construction Demonstration/Technology Transfer

The CLSM test mixtures manufactured in Task I and Task II generated the necessary experimental and production data to optimize CLSM mixture proportions for commercial production. Two construction demonstration/technology transfer workshops were held in Illinois. In order to promote the use of CLSM using Illinois coal ash, two different geographic locations were selected. One field demonstration was held in Rockford, IL, in cooperation with the Rockford Blacktop Construction Co., and a second demonstration and technology transfer workshop was held in Peoria, with cooperation from the City of Peoria and United Ready-Mix, Inc. Also, as a part of these workshops, handout materials were developed for CLSM products, construction methods and technologies, for commercial and government use. In conjunction with these field demonstrations, a one-day workshop was held at both locations to introduce engineers, area contractors, ready-mixed concrete suppliers, environmental agencies, local and state government personnel, and other potential users to the benefits of CLSM slurry with Illinois coal ash.

The first technology transfer workshop was held in Rockford, IL, on June 20, 2001. The workshop consisted of a one-day seminar presented by Tarun R. Naik, UWM-CBU, and Victor H. Smith, RMC Ewell Industries, Tampa FL, along with representatives of Rockford Sand & Gravel Company. Dr. Naik presented background information on the use of flowable slurry (CLSM), including mixture proportion development, use of by-product materials, etc. He also presented the results of this ICCI project including mixture proportions developed in the laboratory and field, as well as current test results. Mr. Smith presented information on field applications of flowable slurry and economy of using flowable slurry. Mr. Smith's presentations on field applications also included several videos on CLSM and its applications. In conjunction with the technology transfer workshop, a field demonstration was conducted on pouring flowable slurry as well as excavating hardened flowable slurry from a trench that was poured approximately one month prior to the workshop. Table 21 gives the mixture proportions of the CLSM mixture used for the construction demonstration. The amount of cement was increased in the mixture to attempt to approximate a typical long-term compressive strength that may be encountered when excavating CLSM. The strength of this mixture was 190 psi at the age of 25 days (Table 22). During the workshop, a backhoe used for the demonstration was able to excavate the CLSM, but the material was very difficult to excavate using hand equipment. The mixture used for the demonstration on the day of the workshop was similar to the mixture used for demonstrating excavatability, but used less cement.

A total of 67 people attended the Rockford workshop. Registrants included six consultants, five contractors, 10 materials suppliers, 31 government agencies employees, six from education, and seven from industry. Comments on the workshop were very favorable. Several people stated that they would be using flowable slurry for construction projects in the near future.

Table 21: CLSM Field Mixture Proportions of Mixture Used For Demonstration of Excavatability in Rockford, IL

Mixture Number	9
Fly Ash Content, A/(A+R), (%)	34
Fine Crushed Sand Content, R/(A+R), (%)	66
Cement, (lb/yd^3), C	131
Fly Ash, Dry Wt., A, (lb/yd^3), A	800
Fine Aggregate, Dry Wt., (lb/yd^3), R	1535
Water, W (lb/yd^3)	713
Flow (in)	11
Density of Fresh Slurry (lb/ft^3)	117.8

Table 22: Compressive Strength of Field CLSM Mixtures – Excavatability Demonstration

Mixture Number	Fly Ash Content, %	Fine Crushed Sand Content, %	Compressive Strength, psi					
			Test Age					
			7-days		25-days		145-day	
			Act.	Ave	Act.	Ave	Act.	Ave.
9	34	66	80	80	200	190	480	495
			80		185		510	
			75		180		490	

The second technology transfer workshop was held in Peoria, IL, on August 31, 2001. The workshop consisted of a one-day seminar presented by Tarun R. Naik, UWM-CBU, and Bruce W. Ramme, Wisconsin Electric Power Company, Milwaukee, WI. Similar to the Rockford workshop, Dr. Naik presented background information on the use of flowable slurry (CLSM), including mixture proportion development, use of by-product materials, etc. He also presented the results of this ICCI project including mixture proportions developed in the laboratory and field, as well as current test results. Mr. Ramme presented information on field applications of flowable slurry, and economy of using flowable slurry. Mr. Ramme also presented information on Wisconsin Electric Power Company's ash utilization program. A field demonstration on pouring flowable slurry was also conducted at the end of the workshop. The CLSM mixture selected for the demonstration was a 50% Illinois coal ash mixture similar to Series 2, Mixture F3, but with a lower cement content. The workshop held in Peoria, IL also included a roundtable discussion with panel members from the Illinois Department of Transportation, the Illinois Environmental Protection Agency, and the Illinois Department of Natural Resources. This roundtable discussion was added to the workshop program per the request of the ICCI Project Manager. This discussion was very well received. The focus of the discussion was on the use of coal ash in Illinois and the barriers to use in existing IDOT projects as well as the permitted uses and applications of CLSM containing any type of coal ash.

A total of 33 people attended the Peoria workshop. Registrants represented three consultants, two contractors, 13 materials suppliers, six government agencies employees, five from education, and four from industry. Comments on the workshop were very favorable. Several people also indicated that they would be using flowable slurry for construction projects in the near future.

Results of this project will also be presented at other UWM-CBU ash utilization workshops to be held in Wisconsin and elsewhere after the completion of this project. UWM-CBU typically holds ash utilization workshops a minimum of once per year in which various options for coal ash utilization are discussed.

CONCLUSIONS AND RECOMMENDATIONS

Two series of CLSM were initially batched in the laboratory. Series 1 CLSM mixtures were composed of a combination of typical fine crushed sand, Illinois coal ash, and cement. Series 2 CLSM mixtures were composed of a typical concrete sand, Illinois coal ash, and cement. Mixture of both series varied the coal ash and sand content from 0% Illinois coal ash and 100% sand or fine crushed sand, to 100% coal ash without sand. Laboratory mixtures were evaluated for fresh CLSM properties as well as compressive strength and water permeability. The laboratory mixtures were then used as the basis for mixture proportions used for field manufacturing. Series 1 field mixtures were manufactured at the facilities of Meyer Material Co., and Rockford Sand and Gravel, Inc., Rockford, IL; while Series 2 field mixtures were manufactured at the facilities of the United Ready-Mix, Inc., Peoria, IL. The CLSM test mixtures manufactured generated the necessary experimental and production data to optimize CLSM mixture proportions for commercial production. Two construction demonstration/technology transfer workshops were then held in Illinois. Based upon the testing and technology transfer activities conducted for this project, the following recommendations are made for commercial manufacture of CLSM containing Class F fly ash generated from combustion of Illinois coal.

Table 23: Recommended CLSM Mixture Proportions – Series 1

Mixture No.	R1	R2	R3	R4	R5
Fly Ash Content, A/(A+R), (%)	100	67	50	33	0
Fine Crushed Sand Content, R/(A+R), (%)	0	33	50	67	100
Cement, (lb/yd^3), C	95	90	85	80	80
Fly Ash, Dry Wt., A (lb/yd^3)	1950	1160	970	730	0
Fine Aggregate, Dry Wt., R (lb/yd^3)	0	575	970	1440	3195
Water*, W (lb/yd^3)	920	875	800	740	585

*Water should be adjusted to provide flow required for the application.

Table 24: Recommended CLSM Mixture Proportions – Series 2

Mixture No.	R6	R7	R8	R9	R10
Fly Ash Content, A/(A+R), (%)	100	80	50	40	20
Standard Concrete Sand Content, R/(A+R), (%)	0	20	50	60	80
Cement, (lb/yd^3), C	95	90	80	70	60
Fly Ash, Dry Wt., A (lb/yd^3)	1950	1645	1370	1016	574
Fine Aggregate, Dry Wt., R (lb/yd^3)	0	335	1370	1345	2240
Water*, W (lb/yd^3)	920	700	650	575	525

*Water should be adjusted to provide flow required for the application.

REFERENCES

1. Naik, T. R., "Temperature Effects on (Illinois Coal) Fly Ash Concrete", M.S. thesis, 1963.

2. ACI 226 Committee, "Use of Fly Ash in Concrete", ACI Materials Journal, September- October 1987, pp. 381-409.

3. Baker M., Jr, Inc., "Coal Combustion By-Product Utilization Manual", EPRI Report No. CS-3122, Vol. 1, February 1984.

4. Naik, T. R., and Singh, S. S., "Effects of Temperature and Type F Fly Ash on Compressive Strength and Abrasion Resistance of Concrete", Proceeding of the Second CANMET/ACI International Conference on Durability of Concrete, Montreal, Canada, 1991.

5. Berry, E. E., Hemmings, R. T., Langley, W. S., and Carette, G. G., "Beneficiated Fly Ash: Hydration, Microstructure, and Strength Development in Portland Cement Systems."Proceedings of the Third International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, V.M. Malhotra, Ed., ACI Special Publication SP-114, Vol. 1, 1989, pp. 241-273.

6. Mehta, P. K., "Pozzolanic and Cementitious By-Products and Mineral Admixtures for Concrete - A Critical Review", Proceedings of the First International Symposium on the Use of Fly Ash, Silica Fume, and other minerals in Concrete, Montebellow, Canada, V. M. Malhotra, Ed., ACI Special Publication No. SP-79, Vol. 1, 1983, pp. 1-40.

7. Michaud, D. T., "Fly Ash Block - Artificial Reef Project, Phase II: Final Report", Preliminary Cost Assessment, Wisconsin Electric Power Company, Milwaukee, WI, October 1986. (T.R. Naik, consultant for strength and disability study for fly ash concrete masonry blocks, 1982 - 1984).

8. Naik, T. R., and Ramme, B. W., "High Early Strength Fly Ash Concrete for Precast/Prestressed Products", PCI Journal, November-December 1990, pp. 72-78.

9. Naik, T. R., Ramme, B. W., and Tews, J. H., "Pavement Construction with High Volume Class C and Class F Fly Ash Concrete", Published by American Concrete Institute, 1995.

10. Naik, T. R., and Singh, S. S., "Superplasticized Structural Concrete Containing High Volumes of Class C Fly Ash", ASCE Journal of Energy Engineering Division, Vol. 117, No. 2, August 1991, pp. 87-95.

11. Naik, T. R., Sivasundaram, V., and Singh, S. S., "Use of High-Volume Class F Fly Ash for Structural Grade Concrete", Transportation Record No. 1301, TRB, National Research Council, Washington D. C., January 1991, pp. 40-47.

12. Naik, T. R., Singh, S. S., and Hu, W. Y., "High-Volume Fly Ash Concrete Technology", EPRI Report No. TR-100473, March 1992.

13. Naik, T. R., Wei, L., and Singh, S. S., "Low-Cost Ash-Derived Construction Materials: State-of-the-Art Assessment", EPRI Report No. TR-100563, April 1992.

14. Wei, L., "Utilization of Coal Combustion By-Products for Masonry Production", M. S. Thesis, Under Supervision of Tarun R. Naik, The University of Wisconsin-Milwaukee, January 1992.

15. Radian Canada, Inc. and CANMET "Investigation of High-Volume Fly Ash Concrete Systems" EPRI Report No. TR-10315, October 1993.

16. Naik, T. R., and Singh, S. S., "Fly Ash Generation and Utilization - An Overview", Published in the book titled "Recent Trend in Fly Ash Utilization", Ministry of Environment and Forests, Government of India, 1998.

17. Naik, T. R., Ramme, B. W., and Kolbeck, H. J., "Filling Abandoned Underground Facilities with CLSM Fly Ash Slurry", ACI Concrete International: Design and Construction, Vol. 12, No. 7, July 1990.

18. Naik, T. R., and Ramme, B. W., "Low Strength Concrete and Controlled Low Strength Material (CLSM) Produced with High-Lime Fly Ash," Presented and Published at the CANMET/EPRI International Conference on Fly Ash in Concrete, Oct. 1990, Calgary, Alberta, Canada.

19. Naik, T. R., Sohns, L. E., and Ramme, B. W., "Controlled Low Strength Material (CLSM) Produced with High-Lime Fly Ash," Presented and Published at the ACAA 9th International Ash Utilization Symposium, Orlando, FL, Jan. 1991.

20. Naik, T. R., Ramme, B. W. and Kolbeck, H. J., "Controlled Low Strength Material (CLSM) Produced with High-Lime Fly Ash," Presented at the International Conference on the Utilization of Fly Ash and Other Coal Combustion By-Products, Shanghai, China, Sept. 18-20, 1991.

21. Naik, T. R., and Ramme, B. W., "Low Strength Concrete and Controlled Low Strength Material (CLSM) Produced with Class F Fly Ash," Presented and Published at the 1992 Spring Convention, American Concrete Institute, Washington, D.C., March 14-20, 1992.

22. Ramme, B. W., Naik, T. R., and Kolbeck, H. J., "Use of CLSM Fly Ash Slurry for Underground Facilities," ASCE Proceedings on Utilization of Industrial By-Products for Construction Materials, Oct. 24-28, 1993.

23. Naik, T. R., and Singh, S. S., "Development of Manufacturing Technology for Flowable Slurry Containing Foundry Sand and Fly Ash," Technical Report submitted to the University of Wisconsin System Solid Waste Research Council, Madison, WI, Aug. 1994.

24. Adebayo, O. D., "Flowable Slurry Containing Foundry Sand and Fly Ash," M.S. Thesis Under the Supervision of T.R. Naik, University of Wisconsin-Milwaukee, May 1994.

25. Krell, William C., "Flowable Fly Ash", Transportation Research Record No. 1234, January 1989, pp. 8-12.

26. Larsen, Ronald L., "Sound Uses of CLSM's in the Environment", ACI Concrete International: Design and Construction, Vol. 12, No. 7, July 1990, pp. 26-29.

27. Edil, T. B., Sandstorm, L. K., and Berthouex, P. M., "Interaction of Inorganic Leachate with Compacted Pozzolanic Fly Ash", ASCE Journal of Geotechnical Engineering, Vol 118, No. 9, September 1992, pp. 1410 - 1430.

28. Naik, T. R., Kraus, R. K., Sturzl, R. F., and Ramme, B. W., "Design and Testing CLSM Utilizing Clean Coal Ash," The Design and Application of Controlled Low-Strength Materials (Flowable Fill), ASTM STP 1331, A.K. Howard and J.L. Hitch, Eds., American Society for Testing and Materials, 1997.

29. Naik, T. R., and Singh, S. S., "Permeability of Flowable Slurry Materials Containing Foundry Sand and Fly Ash," ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123 No.5, May 1997.

30. Naik, T. R., and Kraus, R. N., "Development of Controlled Low Strength Materials Utilizing Kohler Used Foundry Sand - Phase III and Phase IV Report," A Technical Report submitted to the Kohler Company, January 1997.

31. Ramme, B. W., and Naik, T. R., "Controlled Low Strength Materials (CLSM) State-of-the-Art - New Innovations," Proceedings of the Third CANMET/ACI International Symposium on Advances in Concrete Technology, Aukland, New Zealand, August 1997.

32. Ramme, B. W., and Naik, T. R., "Controlled Low Strength Materials (CLSM) State-of-the-Art," Presented at the 1998 Spring Convention of the American Concrete Institute, Houston, Texas, September 1998.

33. Green, B. H., and Naik, T. R., "Development of Soil-Based Controlled Low-Strength Materials," Presented and Published at the ACCA's 13th International Symposium on the Management and Use of CCPs, Orlando, Florida, January 1999.

34. Naik, T. R., "Manufacture of Controlled Low Strength Materials (CLSM) Incorporating Wood Ashes From Weyerhaeuser," Final Report Submitted to Weyerhaeuser Company, Tacoma, Washington, January 2000.

35. Kraus, R. N., Naik, T. R., and Yu, D., "Development of Controlled Low Strength Materials and Concrete Using High Carbon Fly Ash," Final Project Report Submitted to Wisconsin Electric Power Company, June 2000.

36. ASTM. 2000. Annual Book of ASTM Standards. Section 4, Construction, Vol. 04.01, Cement, Lime, Gypsum; American Society for Testing and Materials, Philadelphia, Pennsylvania.

37. ASTM. 2000. Annual Book of ASTM Standards. Section 4, Construction, Vol. 04.08 and 04.09, Soil and Rock, American Society for Testing and Materials, Philadelphia, Pennsylvania.

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