

SUSTAINABLE DEVELOPMENT USING CONTROLLED LOW-STRENGTH MATERIAL

David Trejo,¹ Kevin J. Folliard,² and Lianxiang Du²

¹Department of Civil Engineering, Texas A&M University, USA

²Department of Civil Engineering, University of Texas at Austin, USA

Abstract

This paper describes the use of controlled low-strength material (CLSM) in the United States, with an emphasis on the use of by-product and waste materials CLSM for infrastructure applications. CLSM is a self-leveling, cementitious material used as an alternative to compacted fill in applications including backfill, utility bedding, void fill, and bridge approaches. A general overview of the technology is presented, including a summary of current practice by state highway agencies in the United States. Discussions are presented on key technical properties of CLSM, including fresh and hardened properties, durability, excavatability, and environmental impact. This paper illustrates the important role that CLSM plays in safely and efficiently using by-product materials in a range of applications.

1. Introduction

Controlled low-strength material (CLSM) is, as defined by American Concrete Institute (ACI) Committee 229, is a self-compacted, cementitious material used primarily as a backfill in lieu of compacted fill [1]. Several terms are currently used to describe this material, including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, K-Krete and other various names.

Controlled low-strength materials are defined by “Cement and Concrete Terminology (ACI 116R)” as materials that result in a compressive strength of 8.3 MPa or less [1]. However, most current CLSM applications require unconfined compressive strength of 2.1 MPa or less. Some researchers consider the range of 0.3 to 1.1 MPa as a good index of sufficient strength and easy future excavation. For applications where future excavations are expected, the excavatability of CLSM is critical and this may determine the success of CLSM in practices such as utility bedding.

CLSM is typically specified and used in lieu of compacted fill in various applications, especially for backfill, utility bedding, void fill, and bridge approaches. Backfill includes applications such as backfilling walls (e.g., retaining walls) or trenches. Utility bedding applications involve the use of CLSM as a bedding material for pipe, electrical, and other types of utilities and conduits. Void-filling applications include the filling of sewers, tunnel shafts, basements, or other underground structures. CLSM is also used in bridge approaches, either as a subbase for the bridge approach slab or as backfill against wingwalls or other elements.

There are various inherent advantages of using CLSM instead of compacted fill in these applications. These benefits include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and the ability to place material in confined spaces. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another advantage of CLSM is that it often contains by-product materials, such as fly ash and foundry sand, thereby reducing the demand on landfills, where these materials may otherwise be deposited. This successful and environment-friendly utilization of by-product and waste materials is important to sustainable development and is the focus of this paper.

2. History of CLSM

Soil-cement has been a widely used material in geotechnical-engineering practices for a long time. CLSM is relatively new and is different from conventional soil-cement. Compaction is usually required for soil-cement, which is not the case for CLSM. One of its earliest applications was carried out in 1964 by the US Bureau of Reclamation as the bedding of the 515-km long pipelines in the Canadian River Aqueduct Project, which runs from north of Amarillo to south of Lubbock, Texas [2]. The material used in that project was called plastic soil-cement. The soil used consisted of local blow sand deposits. A new construction procedure was introduced, and the cost of this project was estimated to be 40 percent less than using conventional backfilling techniques. The productivity was increased from about 120 to 305 m of pipe placed per shift.

In the early 1970s, Detroit Edison Company, in cooperation with Kuhlman Corp., a ready-mix concrete producer in Toledo, Ohio, investigated an alternative to compacted granular fill utilizing fly ash and concrete batching techniques. This new backfill material, called flowable fly ash, was used in several applications in the late 1970s [3, 4, 5]. This material was composed principally of fly ash and typically 4 to 5 percent cement, along with an appropriate amount of water. In the Belle River project, it was estimated that more than \$1 million was saved by using this new material [3]. One impressive and exciting feature of this material was that it

remained cohesive when being placed. Another characteristic was the steep angle of repose when it was placed either above or under water.

Eventually, a company known as K-Krete Inc. was formed. In 1977, four patents for K-Krete were issued to Brewer et al. [6]. A typical K-Krete mixture consisted of 1305 to 1661 kg of sand, 166 to 297 kg of fly ash, 24 to 119 kg of cement, and up to 0.35 to 0.40 m³ of water per m³ of product. The four patents included mixture design, backfill technique, pipe bedding, and dike construction. These patents were sold to Contech, Inc., in Minneapolis, Minn., who ceded the patent rights later to the National Ready Mix Concrete Association (NRMCA) with the stipulation that those rights may not be used in a proprietary manner [6, 7]. Since then, ready-mixed concrete producers and contractors have used similar materials to K-Krete without violating legal regulations.

Following K-Krete's emergence as a replacement material for conventional compacted fill, similar materials have been developed and used throughout the United States and Canada. However, the lack of a centralized source for obtaining and disseminating information within the marketplace appeared to cause confusion and reluctance on the part of the engineering community to use these materials. In response to the proposal of Brewer, ACI Committee 229 was established in 1984 under the title "Controlled Low-Strength Materials (CLSM)." After years of efforts, in 1994, the committee published a report called "Controlled Low Strength Materials (CLSM)," which has been referenced widely. In 1999, the revised edition was published.

In 1998, the American Society for Testing and Materials (ASTM) published a book titled "The Design and Application of Controlled Low-Strength Materials (flowable fill)." The articles in this book represented the state of art and practice of CLSM in the field and in the research laboratory at that time. Different types of waste materials were included in CLSM mixtures to recycle waste and reduce the cost. Currently, there are five ASTM testing standards available for CLSM.

3. Utilization of By-Products and Waste Materials

3.1. Use of coal combustion by-product in CLSM

In 2001, 52% of the electricity in the US was produced by coal fired electric utilities (ACAA website). Fly ash is a by-product of coal combustion and has found uses in a wide range of construction applications, including flowable fill, as shown in Table 1 [19]. Fly ash is used mostly in portland cement concrete, but its use in CLSM has grown considerably in recent years.

Table 1: Fly ash applications in construction, 1996 [ACAA 1996]

Applications	Quantity used (million metric tons per year)	% of total used
Cement production and/or concrete products	7.2	60
Structural fills or embankments	1.9	17
Stabilization of waste materials	1.7	14
Road base or subbase materials	0.63	5
Flowable fill and grouting mixtures	0.27	2
Mineral filler in asphalt paving	0.15	2
Approximate total	11.85	100

Although fly ash has become an important construction material, approximately 70 to 75 percent of the fly ash generated annually is still disposed in landfills [20]. Much of this unused fly ash does not meet specifications for use in portland cement concrete (the dominant application), sometimes because of high percentages of unburned carbon, as measured by the loss on ignition (LOI) test. Values of LOI for fly ash used in concrete are typically limited to four percent, whereas some bituminous fly ashes may have LOI values in excess of 15 to 20 percent. Higher unburned carbon contents increase water demand in concrete, and may significantly increase chemical admixture demand (especially air-entraining agents and superplasticizers). Despite the limitations placed on fly ash for conventional concrete, it has been demonstrated that CLSM can be successfully produced using a wide variety of fly ash types and sources, including high-carbon fly ash that is not permitted in concrete.

ASTM C 618 Class F and Class C fly ashes are commonly used in CLSM, in addition to fly ashes that do not meet these or other specifications. There are numerous benefits of using fly ash in CLSM, including improved flowability, reduced segregation and bleeding, and in many cases, reduced material cost.

Bottom ash is another by-product material of coal combustion. Bottom ash is formed by large noncombustible particles that cannot be carried by the hot gases. These particles descend on hoppers or conveyors, at the bottom of the furnace, in a solid or partially molten condition. Then, the particles gradually cool down to form bottom ash. Bottom ash particles are typically porous and angular in shape. As a by-product material, bottom ash is commonly disposed of in ponds. In this process, bottom ash is passed through a crusher to reduce the size of large particles, and it is transported hydraulically through pipelines to the pond shore. The typical range of particle sizes falls between 75 microns and 25 millimeters. Bottom ash can be used in compacted fill when combined with fly ash [21]. Researchers have successfully used bottom ash in CLSM as the fine aggregate [22].

3.2. Use of foundry sand in CLSM

Foundry sand, a by-product of the metal casting industry, has been studied and used successfully in CLSM and its use has increased in recent years [23-28]. Foundry sand is becoming a more viable candidate for use in CLSM because of its lower cost, increasing availability, and satisfactory performance.

It is estimated that for every ton of metal castings produced and shipped that a typical foundry generates approximately one ton of waste sand [29]. The most commonly used waste foundry sand in CLSM is “green sand,” a term applied when the original sand is treated with a bonding agent (usually clay) to optimize the efficiency of the sand in the molding process. After molding is completed, the sand is discarded, often in landfills, and typically at a cost of \$20/ton to \$40/ton [23].

The Federal Highway Administration (FHWA) has issued a report, “User Guidelines for Waste and By-Product Materials in Pavement Construction,” which covers in detail the use of foundry sand (and fly ash) in CLSM and provides guidelines for its proper usage [20]. The U.S. Environmental Protection Agency (EPA) has also recognized foundry sand, along with fly ash, as suitable materials for CLSM [10].

An issue of concern with using foundry sand in CLSM is the potential for environmental impact caused by leaching of heavy metals present in the foundry sand. Ferrous foundry sands are more commonly used in CLSM because there are concerns about the heavy metals content of non-ferrous foundry sands. The EPA does not recommend the use of non-ferrous foundry sand in CLSM because of concerns over the potential leaching of phenols and heavy metals, such as cadmium, lead, copper, nickel, and zinc [10]. Additional information on leaching and environmental issues related to the use of foundry sands in CLSM is provided later in this paper

3.3. Other by-product materials

In addition to foundry sand and fly ash, other waste or by-product materials have been tested and used in CLSM, including ground granulated blast furnace slag (GGBFS), and crushed glass. Because slag is not intended to be supplementary cementing material in CLSM, there is no requirement on the pozzolanic property, which is caused through fast quenching. Thus, slag with less quality can be included in CLSM mixtures. Colored glass that cannot be recycled by local bottle manufacturers has been crushed to pass a 12.5-mm sieve and was successfully used in CLSM as an aggregate [30]. Phosphogypsum (a by-product of phosphoric acid production; plentiful in Florida, Texas, and Louisiana) has been tested in laboratory CLSM mixtures [31]. However, the EPA does not permit its use in CLSM field applications because of environmental concerns associated with phosphogypsum, which contains Radium 226, a radioactive material.

A recent study by Naik et al. focused on the use of wood ash or combined-fuel ash in CLSM [32]. Wood ash is the by-product material of burning wood materials with the combination of other fuels, e.g. coal, oil, natural gas, and coke, to generate electricity for business use [32]. The researchers found that the combined fuel ashes could be engineered to produce suitable CLSM mixtures.

In summary, provided that by-product materials do not prevent CLSM from achieving relevant performance criteria, and also provided that they are not harmful to the environment, a wide variety of waste and by-product materials will likely be used in future CLSM applications. Engineers with the assistance of researchers should take the responsibility to contribute to the sustainable of civilization by including as many by-product and waste materials into their practice as possible.

4. National Cooperative Highway Research Program CLSM Research

4.1. Project summary

A comprehensive investigation of CLSM, funded by the National Cooperative Highway Research Program (NCHRP) under Project 24-12 and 24-12(1) (“Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches”) was started in 1998 and is expect to conclude in the year 2004. The project has culminated in two reports. One report summarized the state-of-the-art and current practice related to CLSM in 1999 and the other report summarized the findings of a comprehensive laboratory investigation of CLSM in 2001 [8, 9]. Results presented in this part are part of these NCHRP-funded efforts and focus mainly on the use of by-product materials in CLSM.

4.2. Survey on the use of CLSM

CLSM is used by state Departments of Transportation (DOTs) in the United States mainly for backfill, utility bedding, void fill, and bridge approach applications. Other applications for CLSM include bedding for granite curbs, engineered fill, and as a lightweight fill to cover swamp areas. Of the forty-four states that responded to the survey, only two states are not currently specifying the use of CLSM. Fig. 1 shows the current applications of CLSM for each state agency [8]. The dominant applications are backfill and bedding material. The majority of CLSM is produced at ready-mixed concrete plants. According to a 1995 survey, it was found that ninety percent of the 3,000 ready-mixed concrete producers in the United States produce some type of flowable fill [10].

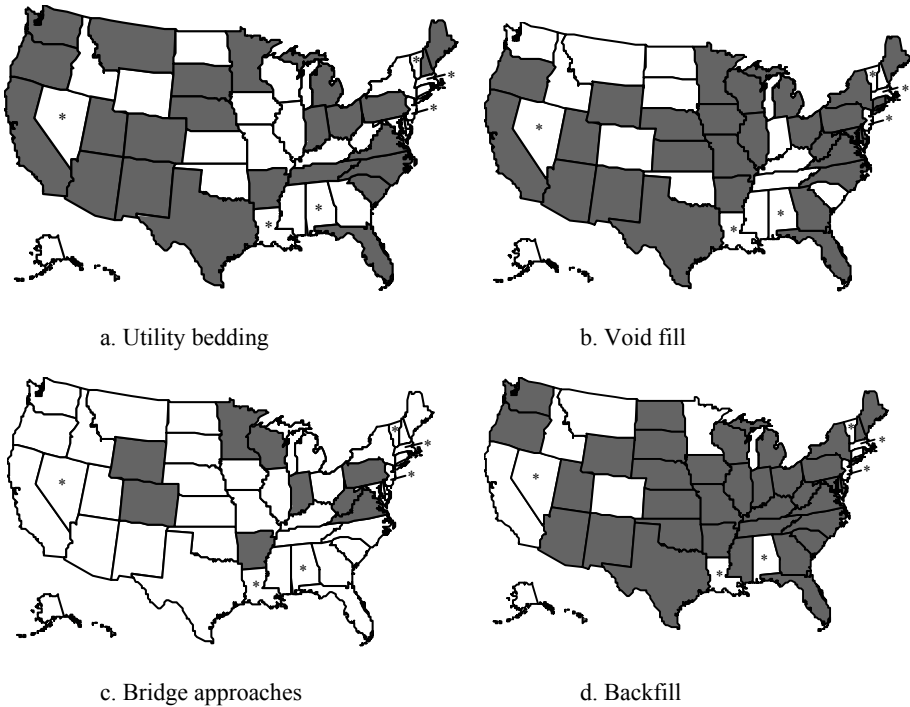


Fig. 1: CLSM application for each state in the United States

4.3. State of practice of CLSM

The benefits of using CLSM as a backfill material are now recognized by at least 42 state DOTs. Engineered CLSM properties are very dependent on the application type. For utility backfill applications, CLSM should be low in strength in the event that the backfill material may require removal for utility repair or replacement. In general, CLSM should be relatively low in long-term strength in order to be excavatable after long durations. Structural backfills do not necessarily require that the CLSM be excavatable, but in some applications this may prove beneficial.

In addition to backfill applications, CLSM is also used as utility bedding and void fill. Advantages of using CLSM as a bedding material include solid, uniform pipe support, reduced labor costs, reduced trench preparation time, and reduction of water ingress to the bedding-pipe interface. One of the largest early applications of CLSM as a bedding material was in 1964 when the U.S. Bureau of Reclamation used a combination of blow sand and cement paste for bedding on 520 kilometers of concrete pipe on the Canadian River Aqueduct Project in Lubbock, Texas [2]. More recently, the city of Denver specified CLSM bedding material for 32 kilometers of

concrete drainage pipe at the Denver International Airport [11]. Currently, twenty-seven states use CLSM for bedding of reinforced concrete, cast iron, ductile iron, corrugated steel, and plastic piping systems. Slightly more than one-quarter of the responding agencies use CLSM predominantly for utility bedding.

Void fill is another common application of CLSM products. Although the majority of states use CLSM for void fill applications (~70%), only seven of the forty-four states stated that using CLSM for void fill was their dominant application. This is most likely because the majority of states have more pipe installation work than void fill work, and not necessarily a result of CLSM being more applicable for bedding/backfill applications than void fill applications. Using CLSM for void fill has proven to be very economical in many cases. Sullivan noted that CLSM can be placed at a rate of approximately 60 m³/hour, at least six times faster than placement of conventional backfill [12]. In addition to the faster placement, the use of CLSM can prevent entry of personnel into confined spaces where safety is of primary importance.

A fairly new application for CLSM is for use as a subbase under bridge approaches. For example, the Delaware Department of Transportation (DelDOT) favors the use of CLSM for many of its bridge approaches. In 1998, the Oklahoma Department of Transportation and Oklahoma State University presented results from a research program that evaluated options to minimize bridge approach embankment settlement [13]. The research program involved construction of three new bridges on U.S. 177 north of Stillwater, Oklahoma. Five different bridge approaches were constructed with different structural fill materials, with one design being a 2.4-m deep CLSM bed. Although there were no reports of differential settlement at the end of the bridge, data collected from the field using indicated that the CLSM settled about 37.5 mm/m. Even though the data indicated that settlement increased until about ten months after placement, the researchers concluded that the majority of the settlement occurred prior to paving. No settlement was observed at the bridge-bridge approach interface. Fox reported that CLSM containing 22-mm maximum size aggregate settled less than 7 mm over a 37-m depth (in a shaft application) [14]. Based on literature and other sources, CLSM appears to be effective, compared to compacted fill, at reducing settlement when coarse aggregates are used.

Due to the high water content of CLSM, subsidence of up to approximately 20 mm/m has been reported. Subsidence is defined as the reduction in volume as a result of losses in water and entrapped air through the consolidation of the mixture. For deep structural fills, subsidence may be significant and contractors should anticipate the reduction in volume. Pons et al. found that CLSM containing accelerators and quick set cement experienced significantly less subsidence [15]. For conventional CLSM, an alternative approach is to initially estimate the subsidence and place the actual elevation of the plastic CLSM above the specified elevation. If

data are available and good engineering is performed the CLSM will subside to the specified elevation. A typical example is if the CLSM subsides 21 mm/m and a placement depth of 3 meters is required, placing the fresh CLSM 63 mm above the finish elevation to compensate for the subsidence should be adequate. After the CLSM subsides, the finish elevation should be attained.

Fig. 2 shows a bridge approach constructed with CLSM at the Cypress reconstruction project in Oakland, California [8]. Polystyrene was used as a filler material to reduce subsidence and reduce the weight of the structural fill. Low density CLSM ($384\text{--}577\text{ kg/m}^3$) was then used on the bridge approaches. The polystyrene was removed after the CLSM hardened to produce the culvert. It is observed in some locations on the CLSM approach bed that the CLSM material had been left higher than the specified elevations. To build the structure to specification, the contractor trimmed the CLSM after hardening using a motor grader. In this case, the proper grade was achieved mostly by placing the CLSM to the proper elevation, but in cases where the CLSM had been left high, trimming was easily accomplished with standard construction equipment.

Using CLSM to reduce settlement at bridge approaches appears to be a simple and reasonably cost effective method that allows for construction flexibility. There have been many successful uses of CLSM in this application that have reduced or eliminated “the bump at the end of the bridge,” which is often encountered as a vehicle leaves the bridge and enters the approach slab. CLSM tends to reduce long-term settlement in this region and increases the service life of the bridge approach system.

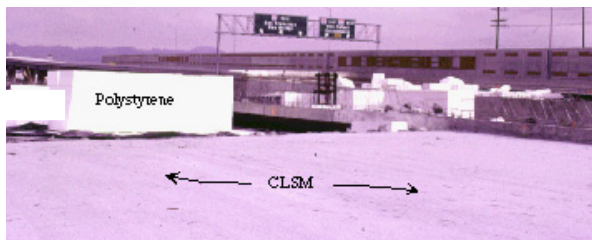


Fig. 2: CLSM used for bridge approach (Oakland, California)

4.4. Engineering properties of CLSM

The following describes some of the technical studies performed on relevant properties of CLSM as part of the NCHRP-funded project. The various studies demonstrate CLSM to be a viable alternative to conventional fill and illustrate the important role by-product materials play in the technology.

4.4.1. Effects of constituent materials on water demand and strength of CLSM mixtures

Research first focused on the effects of material properties on the water demand necessary to obtain minimum flowability values and a range of compressive strength values for CLSM. Three types of aggregate, three types of fly ash, and one ASTM Type I cement were used in this study. Aggregates include river sand, bottom ash and foundry sand. Fly ashes are ASTM Class C, Class F, and off-spec high carbon fly ash. A statistical software was used to optimize the mix design and analyze the results. A total of 31 mixtures were developed and tested. The mixture proportions are shown in Table 2 [16]. The use of different aggregate types and sources was found to be the most significant factor affecting water demand in this investigation, as shown in Fig. 3. Water-cement ratio, aggregate sources, and fly ash type were influencing variables on the compressive strength of CLSM. Equations were developed to predict the compressive strength development of CLSM for the materials used in this research program. The various by-product materials were found to be viable in obtaining the desired CLSM properties.

In summary, the following conclusion were drawn from this study [16]:

- Fine aggregate, especially bottom ash, was the most significant factor affecting the water demand of CLSM.
- The high-carbon fly ash used in this investigation exhibited higher water demand than Class C or Class F fly ash, when used in the same proportions in similar mixtures (a water demand of 315 kg/m^3 for RH33P, compared to 220 kg/m^3 for RF33P). There was no significant difference between the water demands when using Class C or Class F fly ash.
- The variations of fly ash contents used in this study (from 180 and 360 kg/m^3) did not significantly affect water demand.
- The compressive strength of CLSM mixtures varied significantly with specific materials and proportions, especially when the materials increased water demand. For instance, substituting foundry sand for concrete sand in similar mixtures reduced the compressive strength from 3.49 MPa for mixture RF36P to 0.25 MPa for mixture OF36P at 91 days, mainly due to the increased water demand.
- The compressive strength of CLSM can be measured reliably by controlling sample curing, handling, and testing. Of particular importance is selecting a load machine with sufficient accuracy (in the low load range) and control over the load (or deflection, in this case).
- The use of Class C fly ash in CLSM increased the strength considerably when compared with CLSM containing Class F fly ash, mainly due to differences in chemical composition and reactivity (1.12 MPa for mixture OC36P, compared to 0.25 MPa for mixture OF36P at 91 days).

Table 2: Mixture proportions for non-air-entrained CLSM

Mix*	Type I cement (kg/m ³)	Fly ash type*	Fly ash (kg/m ³)	Fine agg. type**	Water demand (kg/m ³)	Flow (mm)	Total bleed (%)	Air content (%)	Unit weight (kg/m ³)
RC13P	30	C	180	CS	211	200	NA	0.9	1965
RC16P	60	C	180	CS	206	200	2.45	0.95	2108
DRC13P	30	C	180	CS	206	210	2.08	0.9	1974
OC33P	30	C	360	FS	486	200	0.13	2.75	1741
BC36P	60	C	360	BA	577	178	4.32	1.65	1754
OH16P	60	H	180	FS	532	240	1.04	3.3	1647
BH13P	30	H	180	BA	628	140	4.81	2.0	1681
OF36P	60	F	360	FS	520	200	0.54	2.5	1684
BF16P	60	F	180	BA	600	178	5.84	2.5	1739
BC33P	30	C	360	BA	572	216	3.64	2.7	1774
RF33P	30	F	360	CS	220	200	0.39	2.2	2199
OF13P	30	F	180	FS	501	200	0.57	2.1	1817
DBC36P	60	C	360	BA	541	200	2.58	2.1	1997
DRF33P	30	F	360	CS	220	216	2.92	1.8	2211
B006H	60	None	None	BA	454	140	1.30	28.5	1382
R006L	60	None	None	CS	200	216	0.70	16.5	1836
RF36P	60	F	360	CS	216	216	1.00	1.3	2174
DRC16P	60	C	180	CS	206	250	0.21	0.5	2291
B003L	30	None	None	BA	582	127	4.35	20.0	1447
BH36P	60	H	360	BA	573	230	6.42	1.7	1743
RH33P	30	H	360	CS	315	200	2.26	1.3	2103
R003L	30	None	None	CS	295	200	2.33	16.0	1922
R003H	30	None	None	CS	170	180	0.62	25.5	1789
R006H	60	None	None	CS	131	200	0.05	26.5	1748
DR006H	60	None	None	CS	136	180	0.43	25.5	1802
DBF16P	60	F	180	BA	600	160	7.20	1.4	1887
DR003L	30	None	None	CS	295	191	2.35	15.5	1874
OC36P	60	C	360	FS	499	200	0	1.8	1902
B003H	30	None	None	BA	492	130	1.08	25.0	1385
B006L	60	None	None	BA	525	130	3.41	18.5	1485
DB006L	60	None	None	BA	525	130	1.44	15.5	1511

* D = repeated mixture; R = river sand; B = bottom ash; O = foundry sand; F = Class F fly ash; C = Class C fly ash; H = high carbon fly ash; P = entrapped air.

** CS=concrete sand; FS=foundry sand; BA=bottom ash.

*** The fine aggregate content was held constant at 1500 kg/m³.

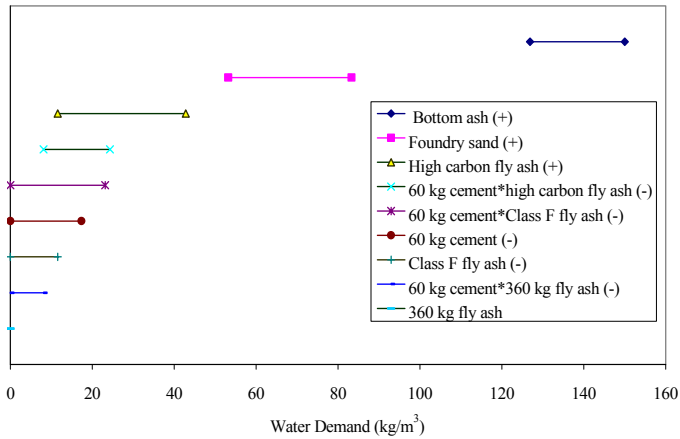


Fig. 3: Pareto-effects graph showing effects of constituent materials on water demand of non-air-entrained CLSM mixtures. The graph shows the deviation from the mean water demand of 446.3 kg/m^3 (+ reflects an increase relative to the mean; - reflects a decrease; no sign indicates that the effect was negligible).

4.4.2. Curing effects on strength development of CLSM mixtures

One important factor hindering the wide acceptance of CLSM is the undesirable long-term excessive strength development. Folliard et al. studied the curing effects on the strengths of CLSM mixtures [17]. Six CLSM mixtures, representing a range of constituent materials and mixture proportions, were included in the study, shown in Table 3. Three curing temperatures (10, 21, and 38 C) and investigated to evaluate their effects on the compressive strength development of CLSM. The splitting tensile strength of selected mixtures was also measured. For each of the curing temperatures, two different relative humidity conditions were assessed to gain an understanding of the effects of temperature and humidity on strength gain at ages of 7, 28, and 91 days. The effects of temperature and humidity were found to largely depend on the constituent materials and mixture proportioning. In particular, the “reactivity” of fly ash was found to be critical in influencing the strength of CLSM mixtures, especially when an ASTM Class C fly ash was used. Some CLSM mixtures containing Class C fly ash exhibited a tremendous increase in strength when cured under the highest temperature condition. Although the dependence of cementitious materials containing fly ash on temperature is well known, the increases in strength of CLSM mixtures containing a high-calcium fly ash (up to a 20x increase in strength for higher temperature curing, i.e., Fig. 4) far exceeded the strength increases typically observed for conventional concrete. CLSM containing fly ash typically has a much higher ratio of fly ash/portland cement and as such, the role of fly ash in strength development is significantly increased. When fly ash was not included in the mixture, i.e., mixture AIR, the effect of high temperature curing was negligible, as in Fig. 5.

Table 3: CLSM mixture proportions for curing effect study

Mixture	Cement content (kg/m ³)	Fly ash type	Fly ash content (kg/m ³)	Concrete sand (kg/m ³)	Water (kg/m ³)	Flow (mm)	Air content (%)	Density (kg/m ³)
FA	60	F	1200	None	492	220	2.4	1631
15F2	15	F	240	1500	197	240	1.2	2191
15C2	15	C	240	1500	175	240	1.4	2212
30C1	30	C	180	1500	181	200	1.2	2163
30F1	30	F	180	1500	188	220	1.4	2210
AIR	60	None	0	1500	123	190	25.5	1603

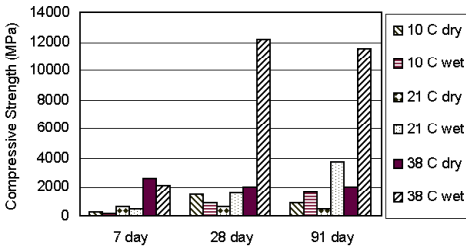


Fig. 4: Compressive strength of mixture 30C1 under different curing conditions

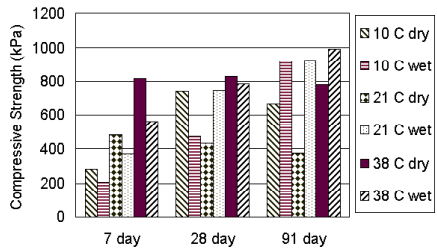


Fig. 5: Compressive strength of mixture AIR under different curing conditions

To emphasize the importance of availability of moisture to the strength development, two curing regimes were employed. Half of the specimens were stripped at the age of three days. The other half specimens were kept in the cast molds until the day of testing. The two scenarios were identified as “dry” and “wet” in the graphs. Under all curing regimes, drying (from an age of three to seven days) generally increased the 7-day strength of CLSM, compared with keeping the cylinders in molds continuously for 7 days. At the age of 91 days, nearly all wet-cured cylinders obtained higher compressive strength than their corresponding dry-cured cylinders at the same curing temperature. This is similar to laboratory air-cured concrete [18]. All dry-cured cylinders at low temperatures (10°C and 21°C) demonstrated strength retrogression from the age of 28 to 91 days. The deteriorating rates of compressive strength were much faster than those of concrete. Dry specimens cured at the high temperature were not significantly affected. But this does not necessarily indicate that these specimens behaved differently from others at low temperatures. It is also possible that these specimens were just at the early stage of strength retrogression at 91 days and the strength could be much lower beyond this age.

An important conclusion from the above investigation is that one must consider the long-term strength gain of CLSM when future excavatability is desired. This importance is paramount when large volumes of fly ash are used in CLSM,

especially if a high-calcium fly ash is used. All types of fly ash can be used efficiently in CLSM, but this research showed that trial mixing and testing of cylinders exposed to similar conditions as anticipated in the field application may be prudent to assure the desired long-term properties and to allow for future excavation of CLSM installations.

4.4.3. Corrosion of ductile iron utilities in CLSM mixtures

Another important factor possibly hindering the use of CLSM is the limited information available to the engineering community on the impact of backfilling pipes with this material. Limited studies have been performed on the impact of CLSM on the corrosion performance of pipe materials. Because of the significant efforts and cost required to repair pipes and the significant disruption to the public as a result of the loss of service or road closure resulting from failures caused by corrosion, utility agencies and municipalities are often reluctant to use materials where durability has not been proven. Thus, an important part of this research was to evaluate the corrosion performance of commonly used pipe materials embedded in CLSM.

To evaluate the corrosion performance of ductile iron pipe embedded in CLSM, ductile iron coupons were embedded in 75 x 150 mm cylinders containing all CLSM mixtures shown in Table 1 except mixtures 10 and 20R. Triplicate samples were exposed to a 3.0% chloride solution for 18 months after 28 days of curing (23±2°C and 98% relative humidity). Control samples included coupons embedded in sand. Fig. 6 shows the sample layout. All 13 x 24 x 4 mm coupons (AWWA C151, Grade 60-42-10) were fabricated from one 300-mm diameter ductile iron pipe. After 18 months, the samples were removed from the exposure solution, the coupons were removed from the CLSM (and sand), and the coupons were evaluated for mass loss following ASTM G1-90. These mass loss values are directly correlated to mean corrosion rate as follows:

$$\text{Mean Corrosion Rate} \left(\frac{\mu\text{m}}{\text{yr}} \right) = \frac{8.76 \cdot 10^7 \cdot W}{A \cdot T \cdot D} \quad (1)$$

where W is the difference in the mass (grams) of the specimen prior to embedment in the CLSM and after removal from the CLSM, A is the original exposed area (mm^2) of the coupon, T is the time of exposure in hours, and D is the metal density ($\frac{\text{grams}}{\text{mm}^3}$). Fig. 7 shows the mean corrosion rate for the coupons embedded in CLSM and sand. With the exception of mixtures R003H and B006H, the coupons embedded in CLSM exhibited significantly lower mean corrosion rates than the coupons embedded in the sand. These findings indicate that when CLSM is used as a pipe backfill material and subjected to aggressive chloride environments, significant reductions in corrosion activity can occur. These reductions in the corrosion activity could result in extended service life expectancies for pipelines.

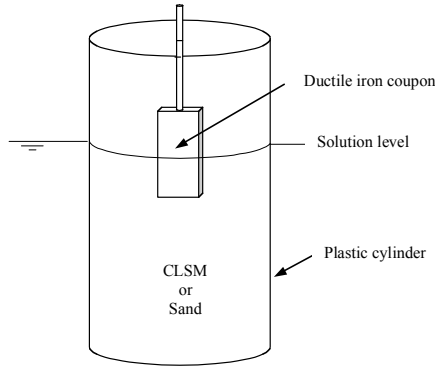


Fig. 6: Sample layout for corrosion testing of ductile iron pipe embedded in CSM & sand

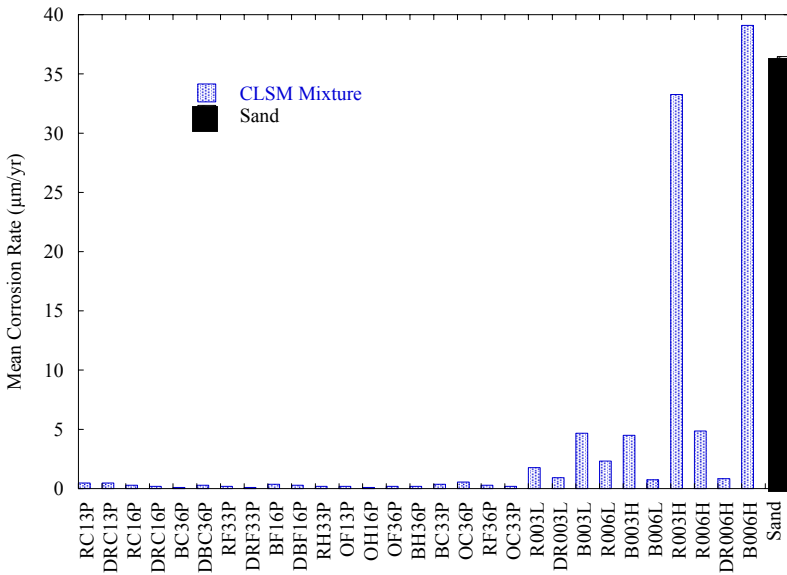


Fig. 7: Mean corrosion rates of ductile iron pipe coupons embedded in CLSM and sand after 18 months of exposure to 3.0% chloride solution

4.4.4. Leaching and environmental impact

The tendency for leaching and subsequent environmental impact may be more critical in the case of CLSM (compared to conventional concrete) because of its higher permeability, and also because of the common use of certain by-product materials, such as fly ash and foundry sand, which may contain heavy metals. Leaching is a relatively slow process and because CLSM is a new technology, sufficient long-term field data and observations are not available to make an informed assessment of CLSM leaching effects.

Research at Purdue University focused on the effects of foundry sands on CLSM leachate and environmental impact [13]. Tests to determine pH and leachate characteristics (using a bioassay method) found that only one of eleven mixtures showed unusually high concentrations of heavy metals in the expressed pore solution. Naik et al. found relatively high concentrations of total dissolved solids in leachate extracted from CLSM containing clean coal ash [22]. Gandham et al. used the toxicity characteristics leaching procedure (TCLP) test (EPA SW-846, Method 1311) to test CLSM containing phosphogypsum [31]. It was found that the toxic contents of the mixtures were well below the EPA leachate standards.

Recent concerns raised by EPA regarding the use of coal combustion products in construction have rekindled the interest in studying the environmental implications of using CLSM containing coal combustion products and other waste materials in the NCHRP 24-12 project [9]. Because the use of by-product and waste materials in CLSM is so common, some research was performed to assess the potential toxicity of materials used in that study and to develop a protocol for assessing materials being considered for use in construction.

The laboratory testing included a full chemical analysis of the by-product and recycled materials included in this project, including fly ash (Class F, Class C, and high-carbon), bottom ash, and foundry sand. The chemical analysis was conducted using inductively coupled plasma emission spectroscopy (ICP), gas chromatography-mass spectrometry (GC-MS), total organic carbon (TOC), and atomic absorption. Information such as the calcium oxide (CaO) content of fly ashes can be very helpful in assessing the potential reactivity and effects on long-term strength gain.

The assessment of the toxicity of the by-product materials used in NCHRP study focused on the identification and quantification of heavy metals. Generally, heavy metals are more of a concern than organics in fly ash, so the limited laboratory study only tested for heavy metals. For each of the by-products included in the study (three fly ashes, one bottom ash, and one foundry sand), the total heavy metal concentration was first determined in accordance with EPA Method 610, where nitric acid and hydrogen peroxide were used to digest the materials. The eight elements analyzed included arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver.

Because this testing determines the total amount of heavy metals, and not the leachable amount, the extraction values may be 20 times the TCLP limits (A “rule of thumb value”). If any of the by-product materials yielded values in excess of the toxicity limits (20 times the TCLP limit), TCLP was then conducted to assess the type and amount of heavy metals that are actually leachable from the materials. Method 40CFR 261.24 was used to extract the samples, and the same 8 heavy metals as previously listed were found.

Testing the raw materials directly, rather than testing the materials encapsulated in CLSM, represents the worst-case scenario for the purpose of toxicity screening. If the constituent materials tested below the TCLP toxicity limits under this worst-case scenario, the materials were classified as non-toxic, and no additional tests were performed. None of the materials tested in this study exceeded the TCLP limits, and thus tests on actual CLSM specimens were not deemed necessary. However, if any materials had exceeded the TCLP limits when tested by themselves, CLSM mixtures would have been cast for subsequent leaching tests. The overall approach to the toxicity and leaching tests performed is shown in Fig. 8.

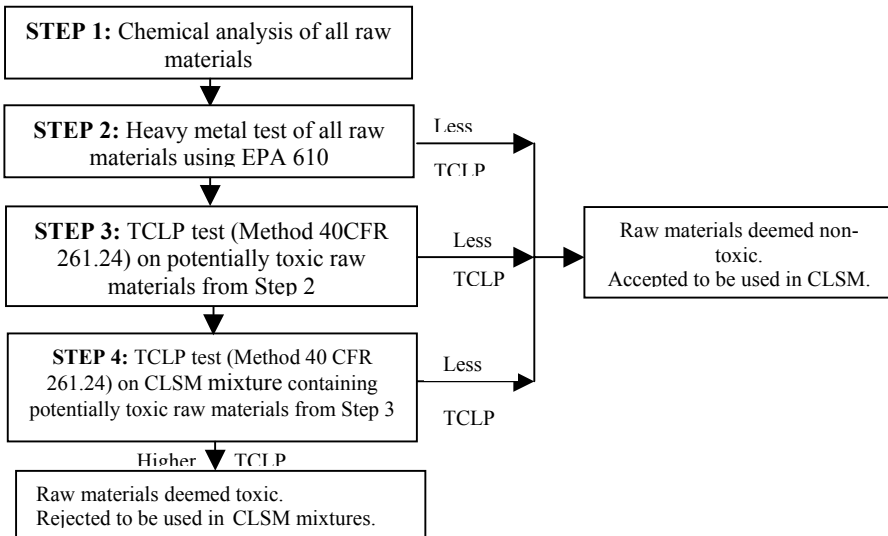


Fig. 8: Flow chart to study toxicity (heavy metals) of CLSM constituent materials

Results representing the total concentration of the eight key heavy metals were obtained. A “rule of thumb” that some practitioners use is that the concentration of total heavy metals can be up to 20 times the standard TCLP limits. According to this guideline, bottom ash, Class C fly ash, and Class F fly ash exceeded the “rule of

thumb” value for arsenic. Thus, additional testing was performed (using the TCLP method) to determine the actual amount of heavy metals that are available to leach from these materials. Because the foundry sand and high-carbon fly ash did not have significant amounts of total heavy metals, the materials were classified as non-toxic, and not subsequent leaching tests were performed.

The TCLP results for Class C fly ash, Class F fly ash, and bottom ash are obtained. The concentration of heavy metals that leached from each material was well below the EPA-recommended TCLP limits, and as such, the materials were classified as non-toxic and suitable for use in CLSM. If any of the by-product materials had exhibited significant leaching of heavy metals (above the TCLP limits), the last step would have been to assess the actual leaching of heavy metals from CLSM containing the material(s). This systematic approach can be followed for any material being considered for use in CLSM. Although all the materials used in this study were deemed non-toxic, it may be possible that certain materials considered for a given CLSM application may be more of an environmental concern.

5. Concluding Remarks

As the construction industry continues to recognize the importance of sustainable development, technologies such as controlled low-strength material have come to the forefront as viable means of safely and efficiently using by-product and waste materials in infrastructure applications. This paper provided an overview of CLSM, with an emphasis on by-product utilization. CLSM usage is increasing significantly in the United States, and the amount and types of by-product materials being used continues to increase. It is hoped that this paper provides useful information for those considering CLSM as an alternative to compacted fill and as a vehicle for implementing by-product materials in infrastructure applications to promote sustainable development.

References

1. American Concrete Institute, Committee 229, Controlled Low-Strength Materials (CLSM), ACI 229R-94 Report, 1994.
2. Adaska, W. S., “Controlled Low Strength Materials,” *Concrete International*, Vol. 19, No. 4, 1997.
3. Funston, J. J., Krell, W. C. and Zimmer, F. V., “Flowable Fly Ash, A New Cement Stabilized Backfill,” *Civil Engineering*, ASCE, 1984.
4. Krell, W. C., “Flowable Fly Ash,” *Transportation Research Record*, No. 1234, 1989.
5. Krell, W. C., “Flowable Fly Ash,” *Concrete International*, Vol. 15, No. 7, 1989.
6. Larsen, R. L., “Sound Use of CLSMs in the Environment,” *Concrete International*, Vol. 15, No. 7, 1993.

7. Larsen, R. L., "Use of Controlled Low Strength Materials in Iowa," *Concrete International*, Vol. 10, No. 7, 1988.
8. Folliard, K. J., Trejo, D., Du, L., and Sabol, S. A., "Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches," NCHRP 24-12 Interim report, 1999.
9. Folliard, K. J., Trejo, D., Du, L., and Sabol, S. A., "Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches," NCHRP 24-12(1) Interim report, 2001.
10. Environmental Protection Agency (EPA), "Back Document for Proposed CPG III and Draft RMAN III." *EPA Report EPA530-R-98-003*, 1998.
11. Hook, W. and Clem, D. A., "Innovative Uses of Controlled Low Strength Material (CLSM) in Colorado," *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
12. Sullivan, R. W., "Boston Harbor Tunnel Project Utilizes CLSM." *Concrete International*, Vol. 19, No. 5, 1997.
13. Snethen, D. R. and Benson, J. M., "Construction of CLSM Approach Embankment to Minimize the bump at the End of the Bridge." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
14. Fox, T. A., "Use of Coarse Aggregate in Controlled Low Strength Materials." *Transportation Research Record*, No.1234, 1989.
15. Pons, F., Landwermyer, J. S. and Kerns, L., "Development of Engineering Properties for Regular and Quick-Set Flowable Fill." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
16. Du, L., Folliard, K.J, and Trejo, D., "Effects of Constituent Materials and Quantities on Water Demand and Compressive Strength of Controlled Low Strength Material," *ASCE Journal of Civil Engineering Materials*, Vol. 14, No. 6, 2002.
17. Folliard, K.J, Du, L., and Trejo, D., "Curing Effects on Strength Development of CLSM Mixtures," *ACI Materials Journal*, Vol. 100, No. 1, 2003.
18. Mindess, S. and Young, J. F., *Concrete*, Prentice-Hall, Inc., 1981, pp. 302-304.
19. American Coal Ash Association (ACCA), "1996 Coal Combustion Products: Production and Use." Alexandria, Virginia, 1997.
20. Federal Highway Administration (FHWA), Chesner, W. H., User Guidelines for Waste and By-Product Materials in Pavement Construction. Federal Highway Administration, Turner-Fairbank Highway Research Center, 1998.
21. Karim, A. K., Salgado, R. and Lovell, C. W., "Compaction of Fly and Bottom Ash Mixtures," *51st Purdue Industrial Waste Conference Proceedings*, 1996.
22. Naik, T. R., Kraus, R. N., Sturzl, R. F. and Ramme, B. W., "Design and Testing Controlled Low Strength Materials (CLSM) Using Coal Ash," *Testing Soil*

- Mixed with Waste or Recycled Materials*, ASTM STP 1275, West Conshohocken, PA, 1998.
23. Bhat, S. T., Use of Coal Combustion Residues and Foundry Sands in Flowable Fill, Ph. D. Dissertation, Purdue University, 1996.
 24. Bhat, S. T. and Lovell, C. W., "Mix Design for Flowable Fill," *Transportation Research Record*, No. 1589, 1997.
 25. Bhat, S. T. and Lovell, C. W., "Flowable Fill Using Waste Sand: a Substitute for Compacted or Stabilized Soil," *Testing Soil Mixed with Waste or Recycled Materials*, ASTM STP 1275, West Conshohocken, PA, 1997.
 26. Stern, K., "The Use of Spent Foundry Sand in Flowable Fill in Ohio," *Foundry Management & Technology*, Vol. 123, No.9, 1995.
 27. Tikalsky, P.; Smith, E.; and Regan, R. W., "Proportioning Spent Casting Sand in Controlled Low-Strength Materials," *ACI materials journal*, Vol. 95, No. 6, 1998.
 28. Tikalsky, P., Gaffney, M., and Regan, R., "Properties of Controlled Low-Strength Material Containing Foundry Sand," *ACI materials journal*, Vol. 97, No. 6, 2000.
 29. Kennedy, D. O. and Linne, C. L., "Environmental and Economical Aspects of Sand Reclamation System." EPRI, Vol. 2, Palo Alato, CA, 1987.
 30. Ohlheiser, T. R., "Utilization of Recycled Glass as Aggregate in Controlled Low-Strength Material (CLSM)," *Testing Soil Mixed with Waste or Recycled Materials*, ASTM STP 1275, West Conshohocken, PA, 1998.
 31. Gandham, S., Seals, R.K. and Foxworthy, P. T., "Phosphogypsum as a Component of Flowable Fill." *Transportation Research Record*, No. 1546, 1996.
 32. Naik, T. R., Kraus, R. N., and Siddique, R., "Controlled Low-Strength Materials Containing Mixtures of Coal Ash and New Pozzolanic Material," *ACI Materials Journal*, Vol. 100, No. 3, 2003.
 33. Bhat, S. T. and Lovell, C. W., "Use of Coal Combustion Residues and Foundry Sands in Flowable Fill." School of Civil Engineering, Purdue University, 1996.