PERFORMANCE AND LEACHING ASSESSMENT OF FLOWABLE SLURRY

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ABSTRACT: This project was conducted to evaluate the performance and leaching of controlled low strength materials (CLSM) incorporating fly ash and foundry sand. Two different CLSM (or flowable slurry) reference mixtures (equivalent to available production CLSM mixtures) were proportioned for unconfined compressive strength levels in the range of 0.3–0.7 MPa (50–100 psi), at 28 days, using two sources of ASTM Class F fly ash. For each reference mixture, other mixtures were proportioned using two sources of foundry sand (molten metal-casting mold sand) as a replacement for fly ash in the range of 30–85%. The ingredients of the slurry mixtures—fly ash, clean foundry sand, and used foundry sand—were tested for their physical and chemical properties and their leachate characteristics. Portland cement used as the primary binder was also tested for its properties. All CLSM mixtures made with and without foundry sand were evaluated for settlement, setting and hardening characteristics, compressive strength, permeability, and leachate characteristics. The leachate results of these CLSM-making materials were below the enforcement standards (ES) of the Wisconsin Department of Natural Resources (WDNR) ground-water quality standards (GWQS). They also met practically all the parameters of the drinking water standards. A number of CLSM mixtures incorporating fly ash and foundry sand are recommended for construction applications.

INTRODUCTION

U.S. foundries generate over 7 million tonnes (8 million tons) of by-products per year. Wisconsin alone produces nearly 1.1 million tonnes (1.25 million tons) of foundry by-products, including foundry sand and slag. Most of these by-products are landfilled, primarily due to nonavailability of economically attractive use options, lack of market development, or lack of management interest. Landfilling is not a desirable option because it not only causes financial burden to the foundries, but also makes them liable for future environmental costs, problems, and restrictions associated with landfilling. Furthermore, the cost of landfilling is escalating due to shrinking landfill space and stricter environmental regulations. Foundries are relatively low profit margin industries. In order for them to remain competitive in national and international markets, it is essential to reduce or eliminate the cost of disposal of their by-products. One of the innovative solutions appears to be high volume uses of foundry by-products in construction materials. Naik and his associates (Adebayo 1994; Naik and Singh 1994, 1997a,b; Naik et al. 1996) have reported applications of foundry sand and slag in cement-based materials, including concrete, masonry products, and controlled low strength materials (CLSM). This paper primarily deals with application of used foundry sand in the manufacture of CLSM.

ACI 229 defines flowable slurry as a ''cementitious material that is in a flowable state at placement and has specified compressive strength of 8.3 MPa (1,200 psi) or less at the age of 28 days.'' Flowable slurry is also called a controlled low strength material and is primarily used for nonstructural applications. Experience shows that, in cases where the material may need to be reexcavated in the future, the compressive strength should be between 0.3 and 0.7 MPa (50 and 100 psi). CLSM is used as a backfill material for utility trenches containing ducts and/or pipes, around manholes and other excavations in streets, around foundations, or as a fill for abandoned tunnels, sewers, storage tanks, etc.

Several organic or inorganic hazardous wastes are treated using solidification and/or stabilization processes. In solidification process, waste products are encapsulated in the solidified matrix with very little or no chemical bond. Since the chemistry of a waste is not altered during the solidification process, its constituents can leach when permeation of a liquid occurs through the solidified material. Stabilization refers to a chemical process in which solid wastes become parts of the solidified matrix material due to the creation of a chemical bond. Numerous by-products are used in the manufacture of cement-based materials to derive technical and/or economic benefits. These by-product materials are held in the cement-solidified matrix primarily due to mechanical bond because a negligible chemical bond is created in the cementitious matrix. Therefore, mobile (water-soluble) constituents of by-product materials in cement-based materials are susceptible to leach if a liquid permeates through them.

Permeability of water through cement-based materials decreases with increasing amounts of cement content up to a certain limit for a given mixture proportion. This occurs primarily due to improved pore and grain refinements of the material at a higher cement content, leading to the formation of a denser microstructure of the material. This in turn restricts penetration of water or other liquids. An increase in permeability of a material can cause increased leaching of its mobile components. Since CLSM is a low cement content material, its permeability is substantially higher than normal concrete. Thus, CLSM is more susceptible to releasing its mobile constituents components compared with normal or high strength concretes. By-products such as fly ash and used foundry may also contain hazardous constituents depending upon their source. Consequently, their inclusion in CLSM mixture can increase concentration of hazardous constituents in the material. If contaminant concentrations in the leach water derived from materials made with by-products exceed regulatory limits, their use in Wisconsin (and other states) is prohibited. The major aim of this investigation was to develop CLSM mixtures incorporating fly ash and used foundry sand and to establish their performance and leaching assessment.

RESEARCH SIGNIFICANCE

This research was conducted to establish combined effects of fly ash and used foundry sand on physical and mechanical

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properties of CLSM and to evaluate leachates of CLSM made with these by-products. The results of this investigation were to be used to proportion CLSM mixtures incorporating fly ash and used foundry sand for construction applications in Wisconsin. CLSM mixtures meeting the strength requirement with a favorable environmental assessment were to be recommended for commercial applications. This will lead to large-scale use of CLSM, which can consume most of the fly ashes and used foundry sands generated in the United States.

PREVIOUS WORK

Several investigators have published reports and papers in the development of CLSM mixture proportions (Naik et al. 1990; Naik and Ramme 1990; Ramme et al. 1993, 1994; Naik and Singh 1994) and others (GAI Consultants 1988; Krell 1989; Amon 1990; Larson 1990; Smith 1991; ACI Committee 229R-94 1994) to develop CLSM mixtures. Excavatable slurry mixtures with strengths ranging between 0.3 and 0.7 MPa (50 and 100 psi) at the age of 28 days are generally used. However, there is a lack of information on properties of CLSM incorporating foundry sand (Naik and Singh 1994). A few studies (GAI Consultants 1988; Smith 1991; Naik and Singh 1994, 1997b) have evaluated the permeability of CLSM mixtures. The excavatible CLSM materials have shown permeability comparable to or lower than compacted granular fills, ranging between 10^{-4} and 10^{-5} cm/s (ACI Committee 229R-94 1994). GAI Consultants (1988) found permeability for Class F fly ash slurry material ranging from 1.9×10^{-6} cm/s for 5% cement CLSM slurry to an averge of 3.3×10^{-7} cm/s for 20% cement CLSM slurry.

Nagle et al. (1980) reported that the pH of a leachate is a dominant factor influencing solubility of several heavy metals. Ham et al. (1981) evaluated leaching characteristics of used foundry sand. The results revealed that: (1) leaching potential was greatly influenced by the process temperature, and the greatest matter release was observed for the foundry sand not subjected to process temperature; and (2) constituents of the leachates depended upon the type of foundry sand, which reflected the differences in the binder material present in the waste material. Ham et al. (1990) compared the leachate quality in foundry landfills with samples taken from above the zone of saturation. Their results indicated that leachates from the unsaturated zone had relatively low concentrations of contaminants with respect to drinking water standards for all contaminants except iron, manganese, and fluoride; and a leach test conducted on auger waste samples was more accurate in predicting field leachate compositions than the leach test on a raw composite waste.

Triano and Frantz (1992) evaluated concrete made with municipal solid waste combustion fly ash from both the refuse-derived fuel and mass burn plants using the EP-Toxicity test method. The results showed that a very small amount of heavy metal leached from the concrete in spite of the high total concentration of heavy metals.

Fero et al. (1986) determined concentration of organic compounds in ground water leached from an iron foundry landfill. Test samples derived from all monitoring wells showed all measured organics below their respective detection limits. Engroff et al. (1989) evaluated leachate characteristics of foundry sands derived from nine common core binder systems using the toxicity characteristic leaching procedure (TCLP) test method. The test data showed the presence of a wide range of organic compounds, but their concentrations were low. Ham et al. (1993) summarized the results of the above leachate investigations carried out at the University of Wisconsin-Madison.

Hamm et al. (1981) determined leachate concentrations of cadmium, chromium, and lead for samples obtained from cupola dust or sludge from gray iron foundries. Their results showed that cupola dusts or sludge from 9 of 21 factories were EP toxic. Most likely, the processes that produced EP toxic cupola dust or sludge were electric arc furnaces and/or from baghouses. This was partly attributed to the finer and more acidic nature of these wastes than wastes from other processes tested. Traeger (1987) investigated leaching potential of foundry by-products material using both the TCLP and American Foundrymen's Society (AFS) leachate test techniques. For comparison, leach tests were also conducted on native soils from Wisconsin. In general, constituents leached from foundry sands were lower than the native soils. The concentrations of substances leached from native soil were either comparable to or higher than that for foundry sand. The results further indicated that foundry sand was nonhazardous per Resource Conservation and Recovery Act (RCRA) criteria.

Leachate test results on fly ash and cement samples (Pflughoeft-Hassett 1993a) showed all elements below the RCRA limits and many of them even below primary drinking water standards (DWS). Another investigation by Pflughoeft-Hassett et al. (1993b) did not exhibit any adverse effects on ground water due to inclusion of 70% fly ash in a concrete pavement.

American Engineering Testing, Inc. (1992), evaluated leachate characteristics of fly ash, spray dryer material, and bottom ash/slag. The TCLP leach data, except for barium, showed elemental concentration at or below their corresponding DWS. Both ASTM and TCLP leach data exhibited similar results for most elements. The TCLP data showed a high concentration of barium and a lower concentration of boron compared with the ASTM leach data.

MATERIALS

Sand

Both clean (unused) and used foundry sands were incorporated in this investigation. The clean sand (typically used by foundries for sand molds) was obtained from a sand mining company in Berlin, Wisconsin (Badger Mining Corp.), and the used foundry sand was obtained from a steel foundry company (Maynard Steel Casting Corp.) in Milwaukee, Wisconsin. For purposes of comparison, properties of regular concrete sand (meeting ASTM C 33 requirements for use in making concrete) were also measured. Physical properties of these three foundry sands were determined using the appropriate ASTM standard. However, a modified ASTM C 88 was used to measure soundness of the foundry sands. In accordance with the ASTM C 88 test standard, the test sample shall be such that it contains 100 grams of all materials retained on each of the No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 μm), and No. 50 (300 μm) sieves and respectively

TABLE 1. Physical Properties of Sand

Parameter (1)	ASTM (2)	Sand 1 (3)	Sand 2 (4)	Sand 3 (5)
As received moisture content (%)	C 566	0.39	0.19	0.25
Unit weight (kg/m^3)	R 29	1,840	1,730	1,784
Bulk specific gravity	C 128	2.43	2.38	2.44
Bulk specific gravity, SSD	C 128	2.47	2.50	2.57
Apparent specific gravity	C 128	2.52	2.70	2.79
SSD absorption (%)	C 128	1.0	4.9	5.0
Void (%)	C 29	25.0	33.8	34.8
Fineness modulus	C 136	3.57	2.33	2.32
Clay lumps and friable particles (%)	C 136	0.2	0.1	0.4
Soundness of aggregates (%)	C 88	10.0	10.5	54.9
Material finer than #200 (75 μm) sieve	C 117	1.40	0.17	1.08

Note: Sand 1 = regular concrete sand; Sand 2 = clean foundry sand (FS1); Sand 3 = used foundry sand (FS2).

passing through sieves 9.5 mm (3/8 in.), No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), and No. 30 (600 μm). Since foundry sand is finer than the No. 30 sieve, only about 0.2–2.1% of the clean and used foundry sands was retained on the No. 4 (4.75 mm) to No. 30 (600 μm) sieve. Therefore, the ASTM sample requirement was modified to evaluate the soundness of the foundry sands for this investigation. Only one sample was used [100 grams passing through the No. 30 (600 μm) sieve and retained on the No. 50 (300 μm) sieve]. The physical properties data for the regular concrete sand and the two foundry sands are shown in Table 1.

The properties of used foundry sand vary due to the type of foundry processing equipment used, the type of additive for mold making, the number of times the sand is reused, and the type and amount of binder used. The unit weight of the used sand was greater than that of the clean sand, which may be attributed to the finer gradation, attached particles of such materials as steel pellets bonded to the sand during the foundry process, bentonite clay binder material, etc. Both the clean and used foundry sands exhibited high saturated surface dry (SSD) absorption values compared with the regular concrete sand. However, the difference between the values for clean and used foundry sand was insignificant.

The materials finer than the No. 200 (75 μm) sieve were slightly higher for the used foundry sand relative to the clean foundry sand. This difference in the result was probably due to the presence of binders in the used foundry sand. The ASTM limit for a deleterious substance in fine aggregate is 5% for all categories of concretes (for concrete subjected to abrasion, it is limited to 3%). The results for the sand used for this project showed low values of clay lumps and friable particle for all sands tested; all the values were less than the allowable ASTM limit. However, the used foundry sand had the highest value of all the sands tested. This is primarily because of the presence of bentonite clay binder in the used foundry sand, which probably separated from the foundry sand during the soaking in water for 24 hours, and was washed away when sieved in accordance with ASTM C 142.

The mass losses suffered were 10% for the regular concrete and 10.5% for the clean foundry sand when subjected to the soundness test in accordance with ASTM C 88. Thus, both the sands showed values below the ASTM limit of 12%. However, the loss for the used foundry sand was very high (54.9%). This occurred because the used sand particles were weakened due to temperature shock that occurs during molding operations, as revealed by scanning electron microscope (SEM) photomicrographs (Naik and Singh 1994). This led to cracking and, therefore, quicker deterioration of the used foundry sand particles in the soundness test per ASTM. Other factors such as presence of various chemical elements in the used foundry sand could have also influenced the performance of the foundry sand in the ASTM C 88 test.

The sieve analysis grading curves are plotted in Figs. 1 and 2, along with the ASTM standard grading requirements for regular sand used in concrete mixtures. These plots exhibit that both the clean foundry sand and the used foundry sand are finer than regular concrete sand and they are outside the ASTM limits for use in making concrete. The grading curves show that the foundry sands contain predominantly finer particles compared with those of regular concrete sand. Approximately 50–60% of the clean and used foundry sands passed through the No. 50 sieve (95–100% passed the No. 30 sieve). However, when regular concrete sand was replaced with 30% foundry sand, the resulting curve was close to the upper allowable ASTM limit (Fig. 2).

Fly Ash

Two ASTM Class F fly ashes (designated as F1 and F2), obtained from two different sources in Wisconsin, were used in this work. Their physical properties were determined in accordance with ASTM C 311. All the physical properties of the fly ashes, except the Strength Activity Index at 7 days for fly ash F1 and loss on ignition for fly ash F2 (Naik and Singh 1994), satisfied the requirements of ASTM C 618 for Class F fly ash. The chemical composition data for these fly ashes are reported in Table 2.

Cement

Type I cement was secured from one source (Lafarge Cement Co.) and was used throughout this investigation. Its physical and chemical properties were determined in accordance with applicable ASTM test methods. The cement met the ASTM C 150 specifications for Type I cement. The chemical composition data for the portland cement used in this work are shown in Table 2.

MIXTURE PROPORTIONS FOR FLOWABLE SLURRY

In this work, two reference flowable fly ash slurry mixtures were used. The first was proportioned with fly ash F1 for flow

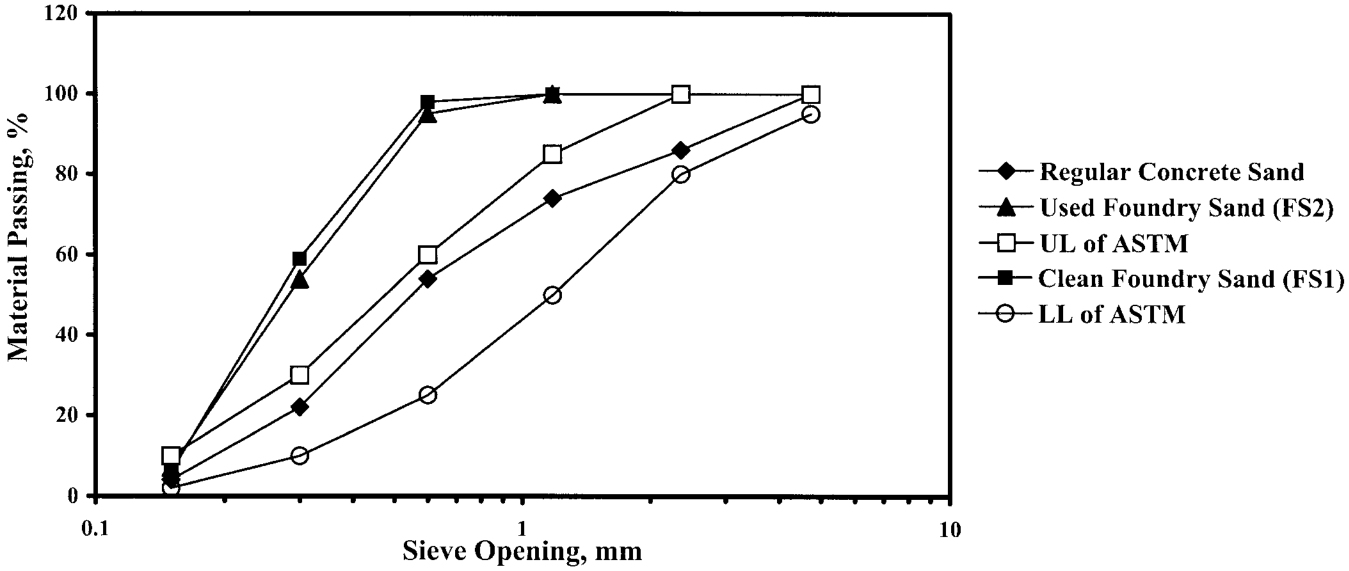


FIG. 1. Sieve Analysis Envelope for Regular Concrete Sand and Foundry Sands

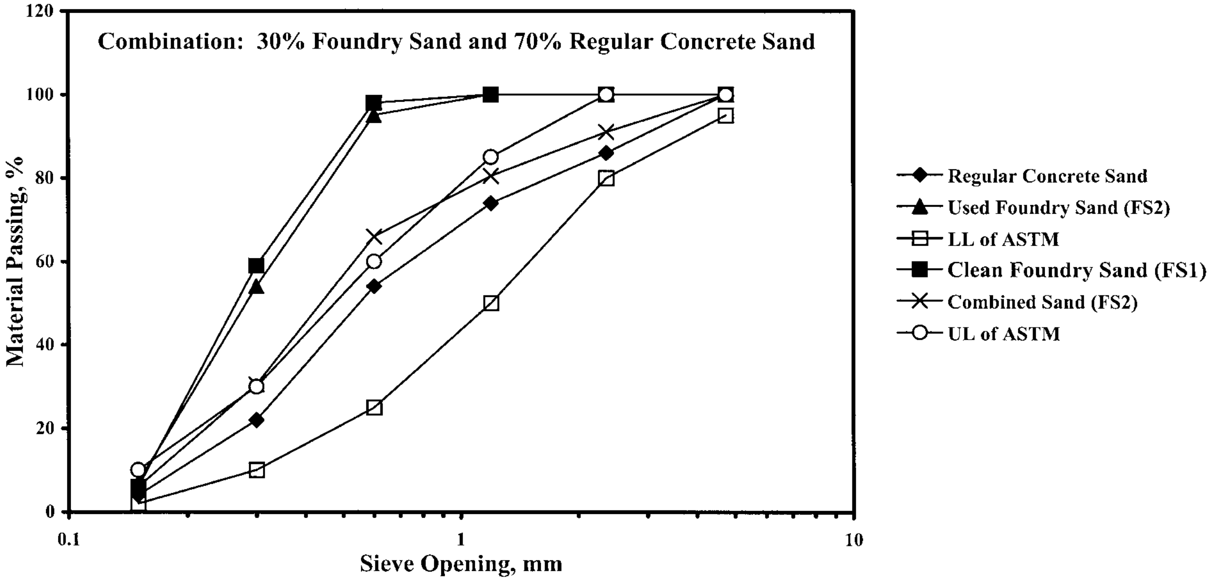


FIG. 2. Sieve Analysis Envelope for Foundry Sand Combined with Regular Concrete Sand

TABLE 2. Chemical Composition of Portland Cement and Fly Ash

Analyte (1)	Cement (%) (2)	ASTM C 150 Type I (%) (3)	Fly ash F1 (%) (4)	Fly ash F2 (%) (5)	ASTM C 618 Class F (%) (6)
SiO_2	20.3	—	48.4	46.1	—
Al_2O_3	4.3	—	27.0	24.4	—
Fe_2O_3	2.6	—	6.6	21.6	—
Total, $SiO_2 + Al_2O_3 + Fe_2O_3$	27.2	—	82.0	92.1	70.0 min
SO_3	—	—	0.6	1.5	5.0 max
MgO	2.2	6.0 max	2.0	1.0	5.0 max
CaO	63.6	—	8.5	3.2	—
TiO_2	0.3	—	1.3	0.9	—
K_2O	0.80	—	1.0	1.4	—
Na_2O	0.20	—	0.5	0.6	1.5 min
Moisture content	—	—	0.2	0.4	3.0 max
Loss on ignition	0.6	3.0 max	2.8	10.7	6.0 max

of 400 ± 25 mm (16 ± 1 in.). The second mixture was proportioned with fly ash F2 for flow of 280 ± 50 mm (11 ± 2 in.). Both mixtures were proportioned to obtain a flowable slurry, as defined by ACI Committee 229R-94 (1994). For each reference mixture, additional mixtures were proportioned with foundry sand as a partial replacement of fly ash. All mixtures were proportioned to have 28-day compressive strength in the range of 0.3–0.7 MPa (50–100 psi). A total of 18 different fly ash slurry mixtures were proportioned and produced at the UWM Center for By-Products Utilization (UWM-CBU) Cement and Concrete Research Laboratory. Of these, two were the control mixtures without foundry sand, and the remaining sixteen had four different replacement levels of fly ash (30, 50, 70, and 85%) with two types of foundry sand (clean and used). The replacement of fly ash by the foundry sand was on a mass basis. The mixture proportions are presented in Tables 3 and 4. The flow/spread was determined in accordance with the ACI 229R-94 (1994) method as reported earlier by Naik et al. (1990).

MANUFACTURING TECHNIQUE

All the constituent materials for the slurry mixtures were mixed using a 0.16 m^3 electrically driven revolving-drum mixer. At the present time, a standard mixing procedure for flowable slurry is not available. As a result, the mixing procedure, as described below, was developed by the writers at UWM-CBU as reported earlier (Naik et al. 1990). For the control mixtures without foundry sand, the inside of the mixer was initially sprayed with water, then the mixer drum was drained of any excess water. All the cement and half of the mixing water were added in the mixer and mixed for three minutes. Then, half of the fly ash was added and mixed for three more minutes. The remaining water and fly ash were alternately added in smaller quantities to obtain the required consistency. Finally, the entire batch was mixed for five more minutes. For all other mixtures, after spraying the mixer with water and draining the excess water, all the foundry sand and cement were mixed together for three minutes, then half of

TABLE 3. Mixture Proportions and Fresh Slurry Properties for Fly Ash F1 Mixtures

Parameter (1)	S1 (2)	S2 (3)	S3 (4)	S4 (5)	S5 (6)	S6 (7)	S7 (8)	S8 (9)	S9 (10)
Foundry sand[a] (%)	0	30(FS1)	50(FS1)	70(FS1)	85(FS1)	30(FS2)	50(FS2)	70(FS2)	85(FS2)
Cement (kg/m^3)	36	44	37	35	46	44	37	36	46
Fly ash (kg/m^3)	1,044	899	737	482	244	899	737	490	248
Foundry sand (kg/m^3)	0	398	756	1,149	1,274	405	757	1,104	1,434
Water (kg/m^3)	540	450	406	363	363	450	405	368	369
[W/(C + FA)]	0.50	0.48	0.52	0.70	1.25	0.48	0.52	0.70	1.25
Flow/spread (mm)	413	406	400	406	406	406	406	400	413
Air content (%)	1.2	1.2	0.6	0.6	0.7	1.2	0.8	0.7	0.7
Air temperature (°C)	13.9	11.1	14.4	16.7	14.4	13.9	14.4	14.4	14.4
Slurry temperature (°C)	16.1	16.1	15.6	16.7	16.1	17.2	19.4	17.8	17.2
Slurry density (kg/m^3)	1,621	1,791	1,948	2,027	2,065	1,797	1,932	2,054	2,108

[a] FS1 = clean foundry sand; FS2 = used foundry sand.

TABLE 4. Mixture Proportions and Fresh Slurry Properties for Fly Ash F2 Mixtures

Parameter (1)	P1 (2)	P2 (3)	P3 (4)	P4 (5)	P5 (6)	P6 (7)	P7 (8)	P8 (9)	P9 (10)
Foundry sand[a] (%)	0	30(FS1)	50(FS1)	70(FS1)	85(FS1)	30(FS2)	50(FS2)	70(FS2)	85(FS2)
Cement (kg/m^3)	47	46	44	47	44	47	46	47	45
Fly ash (kg/m^3)	834	795	634	451	242	812	666	478	249
Foundry sand (kg/m^3)	0	356	633	1,105	1,461	549	710	1,166	1,503
Water (kg/m^3)	685	561	507	297	322	361	467	351	311
[W/(C + FA)]	0.78	0.67	0.75	0.60	1.12	0.42	0.66	0.67	1.05
Flow/spread (mm)	298	292	305	305	330	305	311	337	318
Air content (%)	0.8	1.2	0.4	0.5	0.4	1.3	0.5	0.3	0.3
Air temperature (°C)	14.4	34.4	32.8	14.4	16.1	15.5	14.4	16.1	16.1
Slurry temperature (°C)	17.2	18.9	18.3	18.9	19.6	17.2	17.8	19.4	20.6
Slurry density (kg/m^3)	1,567	1,756	1,847	1,900	2,067	1,769	1,906	2,038	2,108

[a] FS1 = clean foundry sand; FS2 = used foundry sand.

the water required was added and mixed for another three minutes. Thereafter, half of the fly ash was added and mixed for three minutes and the remaining fly ash and water were added alternately in smaller quantities. Finally, the entire batch was mixed for five more minutes. The flow/spread, air content, temperature, density, etc., were determined for each test mixture before casting test specimens (Tables 3 and 4).

PREPARATION AND TESTING OF SPECIMENS

For each CLSM mixture, 150 mm diameter × 300 mm cylinders (6 in. diameter × 12 in.) were made for measurement of plastic properties as well as compressive strength of the flowable slurry mixtures. The cylinders were tested for bleedwater, 50 mm long (16 penny) nail penetration, settlement, and shrinkage cracks. Each slurry mixture was placed in 150 × 300 mm cylindrical mold (6 × 12 in.) for measurements of these parameters. The depth of water that accumulated on the surface of the solidified cylindrical mass was taken as a measurement of bleeding. The condition of the set was determined in accordance with a criteria based on the depth of penetration of a 50 mm long (16 penny) nail (Naik et al. 1990). These parameters were determined at 1 hour and 1, 3, 5, 7, 10, and 14 days age. The nail penetration test was performed by applying moderate pressure (22–44 N) on the 50 mm (2 in.) long nail. The settlement was determined by measuring decrease in the height of the solidified cylindrical mass. The unconfined compressive strength of the test mixtures was performed in accordance with ASTM D 4832.

Bulk chemical analysis of fly ash, clean foundry sand, and used foundry sand was carried out using the Neutron Activation Analysis (NAA) method at the University of Wisconsin-Madison.

Leach tests were conducted on fly ash, clean foundry sand, used foundry sand, and CLSM mixtures in accordance with ASTM D 3987. The ASTM leach method was selected because it simulates mobility (leaching) of substances in CLSM that can occur through permeation of water under field conditions. Additionally, the WDNR uses ASTM leach data for granting permits for commercial applications of new construction materials incorporating by-products. In this method (ASTM D 3987), an extract of each by-product materials and CLSM mixture was obtained. Each test sample, weighing about 70 grams, was prepared and added to a two-liter container having a watertight closure. A volume of test water equal to 20 times weight of the waste sample (1,400 mL) was added to the container. The container was continuously agitated for 18 hours at about 20°C. The sample was then allowed to settle for five minutes and the bulk of the aqueous phase was separated from the solid by filtration through a coarse filter paper. The liquid was filtered through a 0.45 μm filter. The resulting extract was analyzed for various constituents using Wisconsin Department of Natural Resources (WDNR) approved test methods.

TEST RESULTS AND DISCUSSION

Plastic Properties

Several plastic properties of CLSM mixtures, such as flow/spread, temperature, unit weight, settlement, bleedwater, shrinkage cracks, and condition of set, were determined (Tables 3 and 4). The unit weight of the slurry material was found to vary in the range of 1,570–2,115 kg/m^3. The mixtures made with fly ash F1 showed some bleedwater at the one hour age, and the bleedwater decreased generally with time up to 14 days. In the case of the fly ash F2 mixtures, all the mixtures except the 85% foundry sand mixtures, exhibited absence of bleedwater even at the one hour age. This may be attributed to the greater fineness of fly ash F2 and the lower amount of water used in these mixtures compared with the fly ash F1 mixtures. All the fly ash F2 mixtures became hard at the age of 5 days.

Generally, because of setting and hardening of the mixtures, the depth of nail penetration decreased with age. Test data showed a slight increase in settlement up to 3 days. Thereafter, the settlement became approximately constant. In general, total settlement was found to be less than 18 mm (3/4 in.) for the F1 mixtures and 3.2 mm (1/8 in.) for the F2 mixtures with and without foundry sand up to 14 days. In order to have settlement less than or equal to 3 mm (1/8 in.), the water content of the mixtures should be maintained so as to have a flow of 275 mm (11 in.) or less. All of the test specimens showed absence of shrinkage cracks up to the 14 day age.

Compressive Strength

The compressive strength increased with age (Figs. 3 and 4). The compressive strength for all slurry mixtures with and without foundry sand varied from 0.17 to 0.4 MPa (25 to 60 psi) at the 7 day age. The compressive strength values ranged from 0.27 to 0.55 MPa (40 to 80 psi) for the fly ash F1 mixtures and 0.3 to 0.6 MPa (45 to 90 psi) for the fly ash F2 mixtures at 28 days (Fig. 3). These values are approximately in the range of compressive strength needed at the age of 28 days, so as to be able to excavate such flowable slurry in the future (after it is used as a backfill).

Generally, compressive strength increased with an increasing amount of foundry sand up to a certain limit, then decreased. The strength data revealed that excavatable flowable slurry with up to 85% fly ash replacement with clean or used foundry sand can be manufactured without significantly affecting the strengths of the reference mixtures.

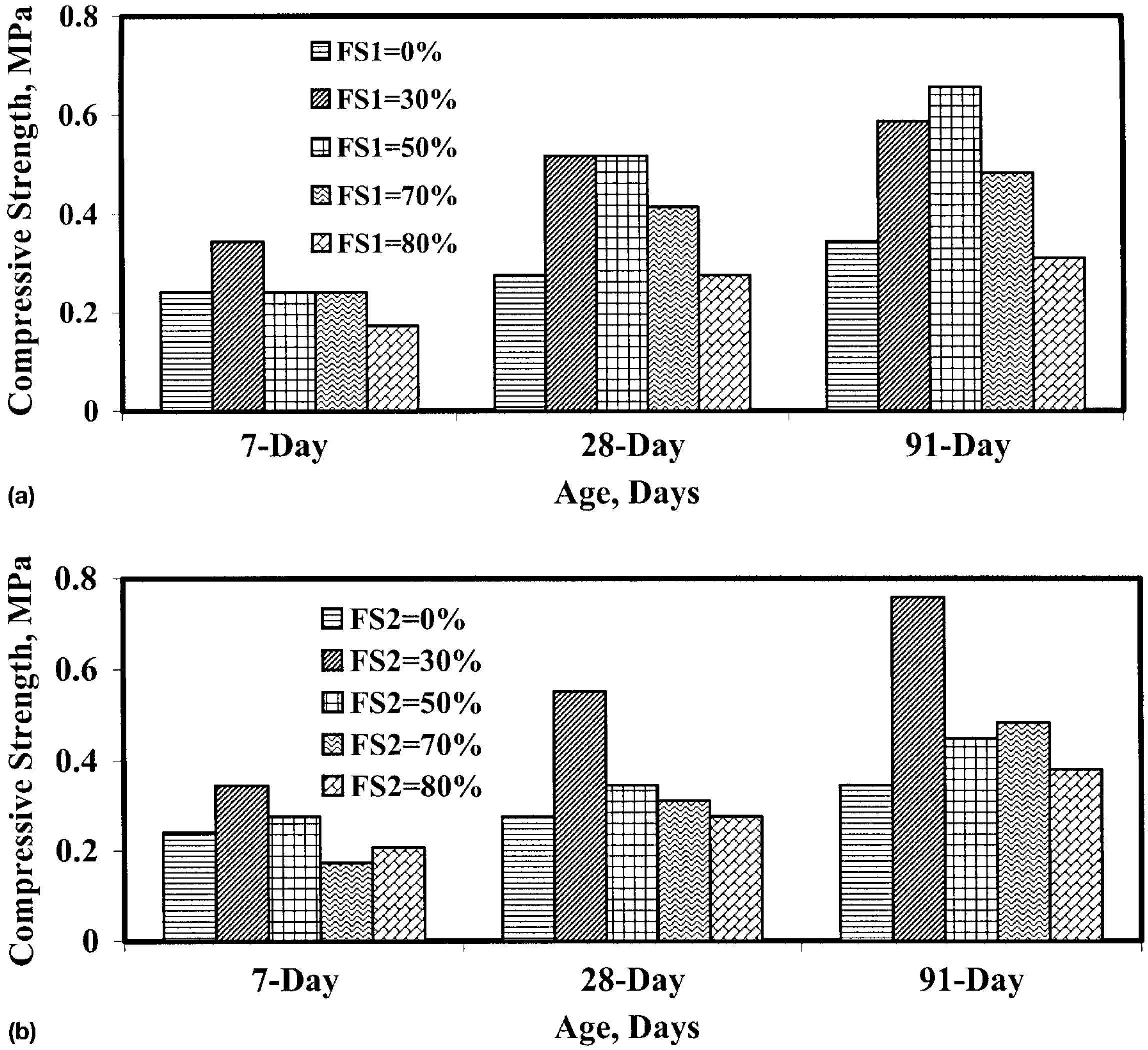


FIG. 3. Compressive Strength versus Age for Fly Ash F1 Mixtures: (a) Clean Foundry Sand (FS1); (b) Used Foundry Sand (FS2)

Permeability

The permeability of the fly ash F1 CLSM slurry mixtures varied from 4×10^{-6} cm/s to 72×10^{-6} cm/s, and for fly ash F2 CLSM slurry mixtures it varied from 5×10^{-6} cm/s to 69×10^{-6} cm/s (Fig. 5). These permeability values are comparable to those observed for granular fill materials. The permeability for both the fly ash reference mixtures were not greatly affected by increasing foundry sand content up to 70% fly ash replacement at the age of 30 days. However, a rapid increase in permeability was observed for the fly ash replacement with foundry sand beyond 70%. This probably occurred because of increases in the size of voids produced by the increase in the amount of foundry sand and decrease in the amount of finer particles of the fly ash in the mixture. Moreover, for lower foundry sand mixtures, i.e., higher fly ash mixtures, a decrease in permeability also occurred due to the densification of the material microstructure resulting from pozzolanic reaction of the fly ash. The effects of source of fly ash and foundry sand on permeability were negligible.

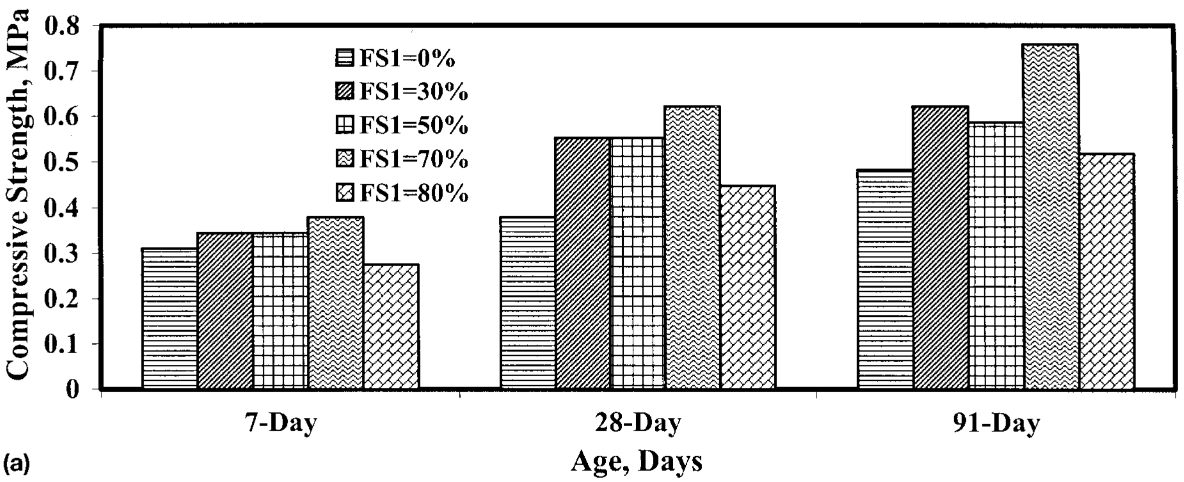
Bulk Chemical Analysis

Elemental concentrations of fly ash, clean foundry sand, and used foundry sand were determined using the Neutron Activation Analysis method. This analysis determined the presence and concentration of chemical elements in these materials, but not their mobility. However, the bulk analysis is of interest in determining the type of constituent materials present and the maximum possible leachate concentration. Such analysis data may be of interest to local environmental regulating bodies (e.g., the Wisconsin Department of Natural Resources) in examining the human health impact of by-product materials.

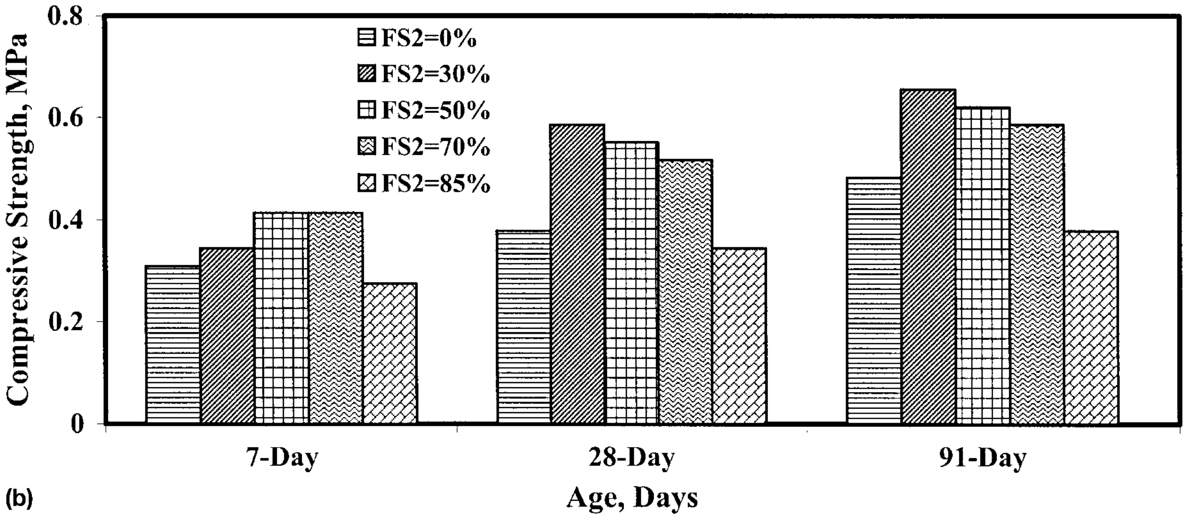
Elemental concentrations of foundry sands have been reported elsewhere (Nail and Singh 1994). The clean foundry sand primarily showed concentration of Si in excess of 500 ppm. The used foundry sand exhibited concentrations of Cr, Hf, Ti, Si, Zr, Fe, Na, and Al above 500 ppm concentration. The used foundry sand exhibited the presence of higher concentrations of several elements, including Dy, Nd, Ce, U, Cr, Hf, Ti, Mg, Cu, Zr, Ni, Fe, Co, Na, Al, Mn, Ca, V, etc., as compared with the clean foundry sand and a lower amount of Si. The additional amounts of these elements entered into the used foundry sand during the mold making and metal casting processes. Other elements in the foundry sands had their maximum concentration less than 500 ppm (Naik and Singh 1994). The bulk analysis of fly ash samples exhibited concentrations of various elements such as Ce, Ba, Ti, Mg, Al, Sr, Rb, Fe, Na, K, La, and Ca above 500 ppm. Numerous other elements present in the fly ash were below 500 ppm (Naik and Singh 1994).

Leachate Characteristics

In this investigation, the ground-water quality standards (GWQS) of the WDNR, especially health-related, were used as a frame of reference for determining performance and



(a)



(b)

FIG. 4. Compressive Strength versus Age for Fly Ash F2 Mixtures: (a) Clean Foundry Sand (FS2); (b) Used Foundry Sand (FS2)

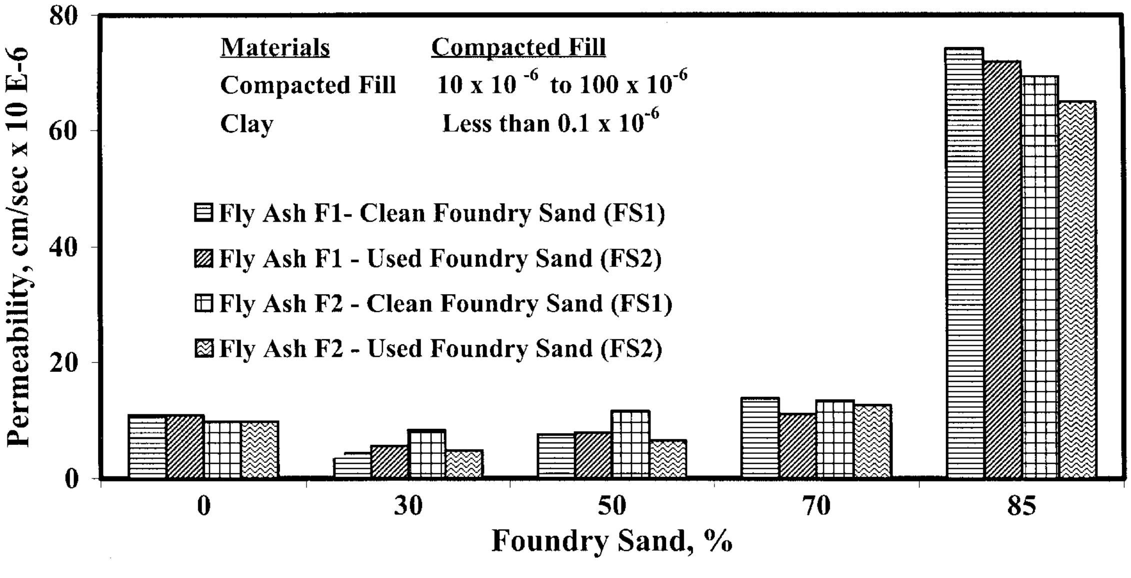


FIG. 5. Permeability of Slurry Mixtures as Function of Foundry Sand Content

leachate assessment of the materials. However, leachate data were also compared with the DWS for comparing leachate quality. The ASTM leach tests were performed (as required by WDNR) on the clean foundry sand, used foundry sand, fly ash F2, and CLSM mixtures made with both foundry sands. Since these materials contained very little organics, leachate derived from each material was analyzed for inorganic constituents in accordance with WDNR requirements (Tables 5–7).

The clean foundry sand met both the WDNR preventive action limit (PAL) and the enforcement standards (ES) of GWQS. The used foundry sand met all parameters of the ES, but it exceeded the PAL for lead and chromium. However, the

TABLE 5. Leachate Analysis of CLSM Ingredients

Parameter (1)	Clean foundry sand, FS1 (mg/l) (2)	Used foundry sand, FS2 (mg/l) (3)	Fly ash, F2 (mg/l) (4)	Drinking water standards (mg/l) (5)	GWQS[a] Enforcement limit (mg/l) (6)	GWQS[a] Preventive action limit (mg/l) (7)
Iron	0.02	0.93	<0.01	—	0.30[b]	0.15[b]
Barium	0.013	0.053	0.12	1.0	2.0[b]	0.4[b]
Manganese	<0.01	0.01	<0.01	—	0.05[b]	0.025[b]
Zinc	<0.01	0.03	<0.01	—	5[b]	2.5[b]
Arsenic	<0.01	0.001	0.074	0.05	0.05	0.005
Chromium	<0.001	0.011	0.051	0.05	0.10	0.01
Lead	<0.001	0.015	<0.001	0.05	0.015	.0015
Selenium	<0.001	<0.001	0.014	0.01	0.05	0.01
Cadmium	<0.0002	0.0002	<0.0002	0.01	0.005	0.0005
Mercury	<0.0002	<0.0002	<0.0002	—	0.002	0.0002
Chloride	<1.8	3	<1.0	—	250[b]	125[b]

Note: — = Not established.
[a]GWQS = ground-water quality standard (public health-related).
[b]GWQS related to public welfare.

TABLE 6. Leachate Characteristics of Fly Ash F1 Mixtures with and without Foundry Sand

Parameter (1)	S1-2(P) (mg/l) (2)	S4-2(P) (mg/l) (3)	S7-2(P) (mg/l) (4)	S8-2(P) (mg/l) (5)	S9-2(P) (mg/l) (6)	Drinking water standards (mg/l) (7)	GWQS[a] Enforcement standard (mg/l) (8)	GWQS[a] Prevention action limit (mg/l) (9)
Foundry sand (%)	0	70(FS1)	50(FS2)	70(FS2)	85(FS2)			
Iron	<0.01	<0.01	<0.01	<0.01	<0.01	—	0.30[b]	0.15[b]
Barium	0.79	0.43	0.88	0.62	0.48	1.0	2.0[b]	0.4[b]
Magnesium	<0.03	<0.03	<0.03	<0.03	<0.03	—	0.05[b]	0.025[b]
Zinc	<0.01	<0.01	<0.01	<0.01	<0.01	—	5[b]	2.5[b]
Arsenic	<0.001	<0.001	<0.001	<0.001	<0.001	0.05	0.05	0.005
Chromium	0.036	0.036	0.018	0.023	0.021	0.05	0.10	0.01
Lead	<0.001	<0.001	<0.001	<0.001	<0.001	0.05	0.015	0.0015
Selenium	0.008	0.005	0.01	0.015	0.007	0.01	0.05	0.01
Cadmium	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.01	0.005	0.0005
Mercury	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	—	0.002	0.0002
Chloride	<1.0	<1.0	<1.0	1	1		250[b]	125[b]

Note: FS1 = clean foundry sand; FS2 = used foundry sand; — = not established.
[a]GWQS = ground-water quality standard (public health-related).
[b]GWQS related to public welfare.

used foundry sand met all requirements, except for Fe, for the public welfare-related GWQS (Table 5). The concentration of iron in used foundry sand was substantially higher than the public-welfare-related ES of the GWQS. The increased iron in the used foundry sand was probably due to the introduction of iron during the metal casting processes.

Both foundry sands met all the requirements for the DWS. The fly ash sample (F2), except for arsenic, met all parameters of the ES. It exceeded the PAL for arsenic, chromium, lead, and selenium. With the exception of selenium, this fly ash also met all parameters of the DWS. The fly ash F2 met all parameters of the GWQS related to public welfare except for iron.

The leachate data for various CLSM mixtures are presented in Tables 6 and 7. Test results revealed that the reference mixture containing only fly ash F1 met all the requirements of the ES and most of the PAL of the GWQS (Table 6). It also met all the parameters of the DWS. With fly ash F1, addition of clean foundry sand caused a slight reduction in selenium concentration of the CLSM mixture containing up to 70% clean foundry sand. Since the clean foundry sand showed absence of selenium, the detected selenium contribution in the CLSM is due to contributions from both fly ash and cement. All the CLSM mixtures met the ES and PAL parameters for public-welfare-related GWQS. The CLSM mixture containing fly ash F2 without foundry sand met all requirements of the ES of the GWQS (Table 7). However, selenium concentration was above the PAL for the mixtures containing up to 70% foundry sand. Except for selenium, these mixtures satisfied the drinking water standards (DWS). The amounts of selenium in the CLSM mixtures were contributed by fly ash F2 and the cement. Generally, addition of both clean and used foundry sand caused reduction in the selenium concentration of the CLSM mixture. Therefore, addition of foundry sand appears to provide favorable environmental performance for the CLSM mixtures.

American Engineering Testing (1992) reported leachate concentrations of coal combustion product materials in the same range as that observed for portland cement and virgin soil. The same was found to be true for slurry ingredients and slurry mixtures tested in this work.

CONCLUSIONS

The following major conclusions are drawn based on data collected in this work:

1. Although the used foundry sand did not pass all ASTM C 33 specifications for fine aggregate for use in concrete, it was found suitable for use in CLSM. The re-

TABLE 7. Leachate Characteristics of Fly Ash F2 Mixtures with and without Foundry Sand

Parameter (1)	P1-8(P) (mg/l) (2)	P3-2(P) (mg/l) (3)	P6-2(P) (mg/l) (4)	P8-2(P) (mg/l) (5)	P9-2(P) (mg/l) (6)	Drinking water standards (mg/l) (7)	GWQS[a]	
							Enforcement standard (mg/l) (8)	Preventive action limit (mg/l) (9)
Foundry sand (%)	0	50(FS1)	30(FS2)	70(FS2)	85(FS2)			
Iron	<0.01	<0.01	<0.01	<0.01	<0.01	—	0.3[b]	0.15[b]
Barium	0.039	0.037	0.011	0.018	0.081	1.0	2.0[b]	0.4[b]
Manganese	<0.01	<0.01	<0.01	<0.01	<0.01	—	0.05[b]	0.025[b]
Zinc	<0.01	<0.01	<0.01	<0.01	<0.01	—	5[b]	2.5[b]
Arsenic	0.042	0.055	0.035	0.028	0.005	0.05	0.05	0.005
Chromium	0.01	0.014	0.014	0.008	0.009	0.05	0.10	0.01
Lead	<0.001	<0.001	<0.001	<0.001	<0.001	0.05	0.015	0.0015
Selenium	0.033	0.022	0.036	0.019	0.009	0.01	0.05	0.01
Cadmium	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.01	0.005	0.0005
Mercury	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	—	0.002	0.0002
Chloride	<1.0	<1.0	<1.0	<1.0	<1.0	—	250[b]	125[b]

Note: FS1 = clean foundry sand; FS2 = used foundry sand; — = not established.

[a] GWQS = ground-water quality standard (public health-related).

[b] GWQS related to public welfare.

sults demonstrated that excavatable flowable slurry incorporating fly ash and foundry sand as a replacement of fly ash up to 85% can be produced.

2. The water permeability of the fly ash CLSM mixtures was relatively unaffected by inclusion of either clean or used foundry sand for fly ash replacement up to 70%. The permeability values of the CLSM mixtures in this investigation were comparable to those observed for typical sand backfill materials. The permeability values ranged from 3×10^{-6} to 74×10^{-6} cm/s.
3. The effect of type and source of fly ash as well as foundry sand was insignificant on compressive strength and permeability.
4. The clean foundry sand showed only one element whose concentration exceeded 500 ppm. The used foundry sand, on the other hand, showed concentrations of elements Cr, Hf, Ti, Si, Zr, Fe, Na, and Ar above 500 ppm.
5. The used foundry sand showed the presence of several elements, including Dy, Nd, Ce, U, Hf, Ti, Mg, Cu, Zr, Ni, Co, Na, Al, Mn, Ca, etc., higher than the clean sand.
6. Fly ash F1 exhibited concentrations of various elements, such as Ce, Ba, Ti, Mg, Al, Sr, Rb, Fe, Na, K, La, and Ca, above 500 ppm.
7. Fly ash F2 met all parameters with the exception of arsenic in the ES of the GWQS and DWS.
8. Both clean and used foundry met the ES of the GWQS. They also satisfied the requirements for the DWS.
9. All slurry mixtures made with fly ash F1 met all the requirements of the Es.
10. All slurry mixtures made with fly ash F2 met all the requirements of the GWQS.
11. In general, inclusion of both clean and used foundry sand caused reduction in concentration of certain contaminants. The use of foundry sand in CLSM slurry, therefore, provided a favorable environmental performance.

RECOMMENDATIONS

Based on the results obtained in this investigation, the following recommendations were made for CLSM mixtures for construction applications:

1. Since both reference fly ash CLSM mixtures (S1 and P1) without foundry sand exhibited favorable environmental performance, these mixtures can be used in construction applications without regulatory restrictions.
2. Excavatable CLSM mixtures meeting the strength requirement (0.3–0.7 MPa) without adverse environmental impact can be proportioned to contain used foundry sand up to 70% of total fly ash in the reference mixtures (mixtures S1 and P1) for construction applications. Such mixtures should include 35–50 kg cement, 240–1,040 kg fly ash, 350–1,170 kg used foundry sand, and 320–685 kg water per cubic meter of the material for a given flow requirement. Due to the lower cost of used foundry sand compared with fly ash, the amount of used foundry sand should be kept high, about 60–70% of total fly ash used in the reference fly ash mixtures.
3. Each source of fly ash and used foundry sand should be evaluated for leaching characteristics prior to their use in CLSM. If leaching characteristics are similar to or better than the ones obtained in this investigation, they can be used in the manufacture of CLSM mixtures for construction applications.

FUTURE WORK

In the present investigation, two sources of an ASTM Class F fly ash and a used foundry sand obtained from a steel foundry company were used to evaluate properties and environmental impact of CLSM mixtures. Additional work is needed in developing CLSM mixture proportions using various types of used foundry sand and coal fly ashes. CLSM mixtures should be proportioned and tested for performance using chemically bonded used foundry sand with Class F fly ash. The effects of ASTM Class C fly ash and fly ashes derived from SOx and NOx control technologies on CLSM mixtures with used foundry sand should also be investigated.

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