

Center for By-Products Utilization

ENVIRONMENTAL PERFORMANCE ASSESSMENT OF FLOWABLE SLURRY INCORPORATING FLY ASH AND FOUNDRY SAND

By Tarun R. Naik, Shiw S. Singh, and Bruce W. Ramme

Report No. CBU-1998-02
March 1998

For Presentation and Publication at the CANMET/ACI International Workshop in
Supplementary Cementing Materials, Superplasticizers and Other Chemical Admixtures in
Concrete, Toronto, Canada, April 1998

Department of Civil Engineering and Mechanics

College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE

ENVIRONMENTAL PERFORMANCE ASSESSMENT OF FLOWABLE SLURRY INCORPORATING FLY ASH SLURRY AND FOUNDRY SAND

by Tarun R. Naik, Shiw S. Singh, and Bruce W. Ramme

Synopsis: This project was conducted to evaluate the environmental impact of Controlled Low Strength Materials (CLSM) incorporating fly ash and foundry sand. Two different flowable fly ash slurry reference mixtures were proportioned for strength levels in the range of 0.3 to 0.7 MPa (50 to 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 as a replacement of fly ash in the range of 30 to 85%.

The ingredients of the slurry mixtures such as fly ash, clean foundry sand, and used foundry sand were tested for their physical and chemical properties, and leachate characteristics. 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 Standard of the Wisconsin Department of Natural Resources (WDNR) Groundwater Quality Standard. They also met practically all the parameters of the Drinking Water Standards.

Generally, compressive strength of the flowable slurry materials increased with age and was found to vary between 0.3 and 0.7 MPa (50 to 100 psi) for the mixtures tested at 28 days. The leachate results of all the CLSM mixtures made with and without foundry sand were below the Enforcement Standard, and they also met practically all the parameters of the Drinking Water Standards. Generally, addition of the foundry sand caused substantial reduction in concentration of the elements that are considered hazardous in accordance with WDNR Groundwater Quality Standard. Therefore, the use of foundry sand may provide favorable environmental impact.

Keywords: chemical analysis, CLSM, compressive strength, controlled low strength materials, environmental performance, flowable fill, flowable slurry, fly ash, foundry sand, leachate, permeability.

ACI Fellow **Tarun R. Naik** is Director of the Center for By-Products Utilization and Associate Professor of Civil Engineering at the University of Wisconsin-Milwaukee. He is a member of ACI Committees 201, Durability of Concrete; 232, Fly Ash and Natural Pozzolans in Concrete; 123, Research; 214, Evaluation of Results of Tests Used to Determine Strength of Concrete; and others.

Shiw S. Singh is a former Research Associate at the Center for By-Products Utilization, at the University of Wisconsin-Milwaukee. He received his Ph.D. in Solid Biomechanics from the University of Wisconsin-Madison. His research interests include mechanical properties and durability of composite materials including concrete made with and without by-products, and soil and groundwater remediation technologies including bioremediation.

ACI member **Bruce W. Ramme** is the Manager of Combustion By-Products Utilization for the Wisconsin Electric Power Company, Milwaukee. He is on the Board of Directors of ACI Wisconsin Chapter; Chairman of ACI Committee 229, Controlled Low Strength Materials and ACI Subcommittee 213C, By-Product Lightweight Aggregate; Member of ACI Committee 213, Lightweight Aggregate and Lightweight Aggregate Concrete; Associate member of ACI Committee 232, Fly Ash and Natural Pozzolans.

INTRODUCTION

U.S. foundries generate over 7 million tonnes (8 million tons) of by-products. 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 non-availability of economically attractive use options. Landfilling is not a desirable option because it not only causes huge 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 associates¹⁻⁵ are involved in developing applications of foundry sand in cement-based materials, including concrete, masonry products, and CLSM. This paper primarily deals with application of used foundry sand in manufacture of CLSM.

ACI 229⁶ defines flowable slurry as a "cementitious material that is in a flowable state at placement and has specified compressive strength of 8.3 MPa (1200 psi) or less at the age of 28 days." Flowable slurry is also called a Controlled Low Strength Material (CLSM) and is primarily used for nonstructural applications. In the cases where the material may need to be reexcavated in the future, the compressive strength should be between 0.3 MPa (50 psi) and 0.7 MPa (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.

Water permeation through CLSM can leach its water soluble constituents. The leachate may join groundwater or other water bodies. If the leachate contains high concentrations of contaminants, it can have polluting influence on them. Before commercial application of this material, it is essential to establish its environmental impact. Therefore, this research was primarily directed towards establishing mixture proportions of CLSM containing foundry sand and evaluating their environmental impact.

PREVIOUS WORK

Naik and his associates⁷⁻¹³ and others^{5, 14-18} have made significant contributions in development of CLSM mixture proportions. Excavatable slurry mixtures with strengths ranging between 0.3 and 0.7 MPa (50 to 100 psi) at the age of 28 days are generally used. However, there is a lack of information on properties of CLSM incorporating foundry sand². A few studies^{2, 5, 17-18} have evaluated the permeability of CLSM mixtures. The excavatable CLSM materials have shown permeability comparable to or lower than compacted granular fills, ranging between 10^{-4} to 10^{-5} cm/sec⁶. GAI Consultants, Inc.¹⁸ found permeability for Class F fly ash slurry material ranging from 1.9×10^{-6} cm/s for 5% cement CLSM slurry to an average of 3.3×10^{-7} cm/s for 20% cement CLSM slurry.

Nagle et al.¹⁹ reported that pH of a leachate is a dominant factor influencing solubility of several heavy metals. Ham et al.²⁰ 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 type of foundry sand which reflected the differences in the binder material present in the waste material. Ham et al.²¹ 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 were more accurate in predicting field leachate compositions than the leach test on a raw composite waste.

Triano and Frantz²² evaluated concrete made with municipal solid waste fly ashes from both refuse-derived fuel and mass burn plants using EP-Toxicity test method. The results showed very small amount of heavy metal leached from the concrete in spite of high total concentration of heavy metals.

Fero et al.²³ determined concentration of organic compounds in groundwater 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.²⁴ evaluated leachate characteristics of foundry sands derived from nine common core binder systems using TCLP test method. The test data showed presence of a wide range of organic compounds, but their concentrations were low. Ham et al.²⁵ summarized the results of the above leachate investigations carried out at the University of Wisconsin-Madison.

Boyle et al.²⁶ determined leachate concentrations of cadmium, chromium, and lead for samples obtained from cupola dust or sludges of gray iron foundries. Their results showed that cupola dusts or sludges from 9 of 21 factories were EP toxic. Most likely, the processes that produced EP toxic cupola dust or sludges 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. Traeger²⁷ investigated leaching potential of foundry waste material using both the TCLP and AFS 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 compared to the Drinking Water Standards (DWS). 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 non-hazardous per Resource Conservation and Recovery Act (RCRA) criteria.

Leachate test results on fly ash and cement samples²⁸ have shown all elements below the RCRA limits and many of them even below primary drinking water standards. Another investigation by Pflughoeft-Hassett et al.²⁹ did not exhibit any adverse effects on groundwater due to inclusion of 70% fly ash in a concrete pavement.

American Engineering Testing, Inc³⁰ 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 high concentration of barium and lower concentration of boron compared to 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 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 foundry sands were determined using appropriate ASTM standards. However, a modified ASTM C 88 was used to measure soundness of the foundry sands. In accordance with ASTM C 88 test standards, 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 μ m), and No. 50 (300 μ m) sieves, and respectively 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 μ m). Since foundry sand used was finer than No. 30 sieve, only about 0.2 to 2.1 percent of the sands was retained on No. 4 (4.75 mm) to No. 30 (600 μ m) 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 No. 30 (600 μ m) sieve and retained on No. 50 (300 μ m) sieve). The physical properties data for the two foundry sands and

regular concrete sand are shown in Table 1.

The properties of used foundry sand vary due to the type of foundry processing equipment used, type of additive for mold making, the number of times the sand is recycled, 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 absorption values compared to the regular concrete sand. However, the difference between the values for clean and used foundry sand was insignificant.

The materials finer than No. 200 (75 μ m) 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 dissolved 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 percent for the regular concrete and 10.5 percent 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 percent. However, the loss for the used foundry sand was very high (54.9 percent). This occurred because the used sand particles were weakened due to temperature shock that occurs during molding operations, as revealed by SEM photo-micrographs (Naik and Singh, 1994). This led to cracking and, therefore, quicker deterioration of the used sand particles in the soundness test per ASTM. However, 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 Fig. 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. The grading curves show that the foundry sands contain predominantly finer particles compared to those of regular sand. Approximately 50 to 60 percent of the clean and used foundry sands passed through the No. 50 sieve (95 to 100 percent passed No. 30 sieve). However, when regular concrete sand was replaced with 30% foundry sand, the resulting curve was close to the upper 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 LOI 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 MATERIALS

In this work, two reference flowable fly ash slurry mixtures were used. The first was proportioned with fly ash F1 for flow 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 (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 the 28-day compressive strength in the range of 0.3 to 0.7 MPa (50 to 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 229 method as reported earlier by Naik et al.⁸.

MANUFACTURING TECHNIQUE

All the constituent materials for the slurry mixtures were mixed using a 0.75 m³ electrically driven revolving-drum mixer. At the present time, standard mixing procedure for slurry is not available. As a result, the mixing procedure, as described below, was developed by the authors at UWM-CBU as reported earlier⁸. For the control mixtures without foundry sand, the inside of the mixer was initially sprayed with water, and 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 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.

PREPARATION AND TESTING OF SPECIMENS

For each CLSM mixture, 150 mm dia. x 300 mm cylinders (6" dia. x 12") 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 (16 penny) nail penetration, settlement, and shrinkage cracks. Each slurry mixture was placed in 150 x 300 mm cylindrical mold (6" x 12") 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 set was determined in accordance with a criteria based on the depth of penetration of a 50 mm (16 penny) nail (Naik et al. 1990). These parameters were determined at 1 hr., and 1, 3, 5, 7, 10, and 14-day 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 compressive strength of the test mixtures was performed in accordance with ASTM D 4832.

Leach tests were conducted on fly ash, clean foundry sand, used foundry sand, and CLSM mixtures in accordance with ASTM D 3987. This method was selected to determine mobility (leaching) of substances due to permeation of water through these material when used in actual construction work.

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. The unit weight of slurry material was found to vary in the range of 1570 to 2115 kg/m³. 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 one hour of age. This may be attributed to the greater fineness of fly ash F2 and lower amount of water used in these mixtures compared to 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 (Fig. 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 specified at the age of 28 days.

Generally, compressive strength increased with increasing amount of foundry sand up to a certain limit, and 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.

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 for 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 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

The bulk chemical analysis was carried out to determine total elemental concentrations of fly ash, clean foundry sand, and used foundry sand. This analysis determines 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 maximum possible leachate concentration. Such analysis data may be of interest to local environmental regulating bodies (e.g. Wisconsin Department of Natural Resources) in examining human health impact of by-product materials.

The clean foundry sand primarily showed concentration of Si in excess of 500 ppm (Table 5). The used foundry sand exhibited concentrations of Cr, Hf, Ti, Si, Zr, Fe, Na and Al above 500 ppm concentration (Table 5). 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., compared to the clean foundry sand and 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 ranged from below their

respective detection limits (BDLs) to maximum concentration less than 500 ppm (Table 5).

The bulk analysis of fly ash samples exhibited concentration of various elements such as Ce, Ba, Ti, Mg, Al, Sr, Rb, Fe, Na, K, La, and Ca above 500 ppm (Table 6). Numerous other elements present in the fly ash were either at very low concentrations or BDL, to maximum concentrations of less than 500 ppm (Table 6).

Leachate Characteristics

In this investigation, the Groundwater Quality Standards (GWQS) of the Wisconsin Department of Natural Resources (WDNR), especially health-related, were used as a frame of reference for determining environmental impact of the materials. However, leachate data were also compared with the Drinking Water Standards (DWS) for comparing leachate quality. The ASTM leach tests were performed on the clean foundry sand, the 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 7 through 9).

The clean foundry sand met both the Preventive Action Limit (PAL) and the Enforcement Standard (ES) of the public health-related GWQS. The used foundry sand met all parameters of the ES, but it exceeded the PAL for lead and chromium. However, the used foundry sand met all requirements, except for Fe, for the public welfare-related GWQS (Table 7). The concentration of iron in used foundry sand was 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 of the GWQS concerning public health. 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 met all parameters of the GWQS related to public welfare for iron.

The leachate data for various CLSM mixtures are presented in Table 8 and Table 9. 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 8). It also met all the parameters of the DWS. With fly ash F1, addition of clean foundry sand caused 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 9). 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 impact for the CLSM mixtures.

American Engineering Testing (1992) reported leachate concentrations of coal combustion by-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. Based on the results obtained, it was concluded that CLSM containing fly ash and foundry sand are environmentally friendly materials.

CONCLUSIONS

The following major conclusions were drawn based on data collected in this work.

1. Although the used foundry sand did not pass all ASTM C33 specifications for fine aggregate for use in concrete, it was found suitable for use in CLSM. The results 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 was 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. Whereas, the used foundry sand 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. The 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. The fly ash F2 met all parameters with exception for arsenic of 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 CLSM 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.
12. All fly ash slurry materials made with and without foundry sand are environmentally friendly materials.

ACKNOWLEDGEMENT

The authors express deep sense of gratitude to the UWS Solid Waste Research Council, Madison, WI; Badger Mining Corp., Berlin, WI; Fall River Foundry Company, Fall River, WI; Maynard Steel Casting Corporation, Milwaukee, WI; Pelton Casteel, Inc., Milwaukee, WI; Stainless Foundry & Engineering, Inc., Milwaukee, WI; Wisconsin Aluminum Foundry Company, Manitowoc, WI; and, Wisconsin Electric Power Company, Milwaukee, WI for their financial support for this investigation.

Special thanks are expressed to Oluwole B. Adebayo for his help in experimental planning, testing, and data collection used in this work. Thanks are also due to the CBU staff, especially Mohammad M. Hossain, Bob Wendorf, Scott Belonger, Michelle Gehrke, and Brian Moen, who directly contributed to the success of this project. Jim Lingle of Wisconsin Electric Power Company's detailed review comments were very useful in improving the overall quality of this paper.

The Center was established by a generous grant from the Dairyland Power Cooperative, La Crosse, WI; Madison Gas and Electric Company, Madison, WI; National Minerals Corporation, St. Paul, MN; Northern States Power Company, Eau Claire, WI; Wisconsin Electric Power Company, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and, Wisconsin Public Service Corporation, Green Bay, WI. Manitowoc Public Utility is also providing a grant to continue the work of the Center. Their financial support, along with the financial support of the Manitowoc Public Utilities, continuing help and encouragement, and active, continuing interest, is gratefully acknowledged.

REFERENCES

1. Adebayo, O.B., Flowable Slurry Containing Foundry Sand and Fly Ash, M.S.Thesis, The University of Wisconsin-Milwaukee, 1994, 126 pages.
2. Naik, T.R. and Singh, S.S., Development of Manufacturing Technology for Flowable Slurry Containing Foundry Sand and Fly Ash, A Technical Report Submitted to the UWS

Solid Waste Research Council, Madison, WI, August 1994.

3. Naik, T.R., Singh, S.S., Tharaniyil, and Wendorf, R.B., Application of Foundry By-Product Materials in Manufacture of Concrete and Masonry Products, *ACI Materials Journal*, Vol. 93, No. 1, 1996, pp. 41-50.
4. Naik, T.R. and Singh, S.S., Permeability of Flowable Slurry Materials Containing Foundry Sand and Fly Ash, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 5, 1997, pp. 446-452.
5. Naik, T.R. and Singh, S.S., Flowable Slurry Containing Foundry Sand, *Journal of Materials in Civil Engineering*, Vol. 9, No. 5, 1997, pp. 93-102.
6. ACI Committee 229R-94, Controlled Low-Strength Materials (CLSM), *Concrete International*, American Concrete Institute, Detroit, MI, July 1994, pp. 55-64.
7. 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, Calgary, Alberta, Canada, October 1990.
8. Naik, T.R., Ramme, B.W., and Kolbeck, H.J., Filling Abandoned Underground Facilities with CLSM Slurry, *Concrete International*, Vol 12, No. 7, July 1990.
9. Naik, T.R., Sohns, L.E., and Ramme, B.W., Controlled Low Strength Material (CLSM) Produced with High-Lime Fly Ash, *Proceedings of the ACAA 9th International Ash Utilization Symposium*, Orlando, FL, January 1991, pp. 9-1 to 9-18.
10. Naik, T.R., Sohns, L.E., and Ramme, B.W., Controlled Low Strength Material (CLSM) Produced with High-Lime Ash, *Proceedings of the International Conference on the Utilization of fly ash and other coal combustion By-Products*, Shanghai, China, September 1991.
11. 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*, October 1993, pp. 41-51.
12. Ramme, B.W., Naik, T.R., and Kolbeck, H.J., Use of Fly Ash Slurry for Underground Facility Construction, *Journal of Construction and Building Materials*, Cambridge, England, January 1994, pp. 63-67.
13. Naik, T.R., and Ramme, B.W., Low Strength Concrete and Controlled Low Material (CLSM) Produced with Class F Fly Ash, *ACI Special Publication SP-150*, American Concrete Institute, 1994, pp.1-9.

14. Krell, W.L., Flowable Fly Ash, Concrete International, Design and Construction, November 1989, pp. 54-58.
15. Larson, R.L., Sound Uses of CLSM in the Environment, Concrete International, July 1990, pp. 26-29.
16. Amon, J. A., Controlled Low-Strength Material, The Construction Specifier, December 1990, pp. 98-101.
17. Smith, A., Controlled Low-Strength Material, Concrete Construction, May 1991, pp. 389-398.
18. GAI Consultant, Inc., Laboratory Testing of Fly Ash Slurry, EPRI Report No. CS-6100, Electric Power Research Institute, Palo Alto, CA, December 1988.
19. Nagle, D.L., Kunes, T.P., and Nichols, D.A., The Role of Waste Characterization in Assessing the Environmental Impact of Existing Landfill - Where Theory Meets Practice, Proceedings of the Third Annual Conference on Applied Research and Practice on Municipal and Industrial Waste, Madison, Wisconsin, 1980.
20. Ham, R.K., Boyle, W.C., and Kunes, T.P., Leachability of Foundry Process Solid Waste, Journal of Environmental Engineering Division, ASCE, Vol. 107, No. EE1, February 1981, pp. 155-170.
21. Ham, R.K., Boyle, W.C., and Blaha, F.J., Comparison of Leachate Quality in Foundry Waste Landfills to Leach Test Abstracts, Journal of Hazardous and Industrial Solid Waste Testing and Disposal, Vol. 6, 1990, pp. 29-44.
22. Triano, J.R., and Frantz, G.C., Durability of Municipal Solid Waste (MSW) Fly Ash Concrete, Journal of Materials in Civil Engineering, Vol. 4, No. 4., November 1992, pp. 369-384.
23. Fero, R.L., Ham, R.K., and Boyle, W.C., An Investigation of Groundwater Contamination by Organic Compounds Leached from Iron Foundry Solid Wastes, Final Report to American Foundrymen's Society, Des Plaines, IL, 1986.
24. Engroff, E.C., Fero, E.L., Ham, R.K., and Boyle, W.C., Laboratory Leachings of Organic Compounds in Ferrous Foundry Process Waste, Final Report to American Foundrymen's Society, Des Plaines, IL, February 1989.
25. Ham, R. K., Boyle, W.C., Engroff, E.C., and Fero, R.L., Organic Compounds in Ferrous Foundry Process, Waste Leachates Journal of Environmental Engineering, ASAE, Vol. 119, 1993, pp. 34-55.

26. Boyle, W.C., Ham, R.K., Pastene, J., and Stanforth, R., Leachate Tests on Selected Foundry Cupola Dusts and Sludges, AFS Transactions, 1981-149, pp. 767-786.
27. Traeger, P.A., Evaluation of the Constructive Use of Foundry Wastes in Highway Construction, M.S. Thesis, The University of Wisconsin-Madison, 1987, 165 pages.
28. Pflughoeft-Hassett, D.F., Hassett, D., and Lillemoen, C.M., Comparative Leaching of Midwestern Coal Fly Ash and Cements, Proceedings of the Tenth ACAA International Ash Use Symposium, Vol. 1, January 1993a, pp. 30-1 to 30-14.
29. Pflughoeft-Hassett, D.F., Hassett, D.J., and Docker, B.A., High Volume Fly Ash Utilization and the Effects on Groundwater in North Dakota, Proceeding of the Tenth ACAA International Ash Use Symposium, Vol. 1, January 1993b, pp. 32-1 to 32-11.
30. American Engineering Testing, Inc., Coal Ash Utilization: A Summary of Current Practices and Economic, Environmental, and Energy Impacts, A Report to Northern States Power Company, July 24, 1992.

TABLE 1: Physical Properties of Sand

Sand 1: Regular Concrete Sand, Sand 2: Clean Foundry Sand (FS1), Sand 3: Used Foundry Sand (FS2)

	As Received Moisture Content, %	Unit Weight, kg/m ³	Bulk Specific Gravity	Bulk Specific Gravity, SSD	SSD Absorption, %	Void, %	Fineness Modulus	Clay Lumps & Friable Particles, %	Soundness of Aggregates, %	Material Finer than 75µm Sieve
ASTM	C566	C29	-----C128-----			C29	C136	C136	C88	C117
Sand 1	0.39	1840	2.43	2.47	1.0	25.0	3.57	0.2	10.0	1.40
Sand 2	0.19	1730	2.38	2.50	4.9	33.8	2.33	0.1	10.5	0.17
Sand 3	0.25	1784	2.44	2.57	5.0	34.8	2.32	0.4	54.9	1.08

TABLE 2: Chemical Composition of the Portland Cement and Fly Ash

Analyte	Cement, %	ASTM C 150 Type I, %	Fly Ash F1, %	Fly Ash F2, %	ASTM C 618 Class F, %
SiO ₂	20.3	---	48.4	46.1	---
Al ₂ O ₃	4.3	---	27.0	24.4	---
Fe ₂ O ₃	2.6	---	6.6	21.6	---
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O 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 ₂ O	0.80	---	1.0	1.4	---
Na ₂ O	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.
------------------	-----	---------	-----	------	----------

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

Mixture No.	S1	S2	S3	S4	S5	S6	S7	S8	S9
Foundry Sand,* %	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	1044	899	737	482	244	899	737	490	248
Foundry Sand, kg/m ³	0	398	756	1149	1274	405	757	1104	1434
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	1621	1791	1948	2027	2065	1797	1932	2054	2108

*FS1 = Clean Foundry Sand; FS2 = Used Foundry Sand.

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

Mixture No.	P1	P2	P3	P4	P5	P6	P7	P8	P9
Foundry Sand,* %	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	1105	1461	549	710	1166	1503
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	1567	1756	1847	1900	2067	1769	1906	2038	2108

*FS1 = Clean Foundry Sand; FS2 = Used Foundry Sand

TABLE 5: Chemical Elemental Analysis for Foundry Sand

Element	Quantity in PPM*		Element	Quantity in PPM*	
	Clean Sand (FS1)	Used Sand (FS2)		Clean Sand (FS1)	Used Sand (FS2)
Aluminum, Al	229	601	Neodymium, Nd	1.944	64.84
Antimony, Sb	0.003	1.56	Nickel, Ni	0	14.380
Arsenic, As	0	0	Osmium, Os	0	0
Barium, Ba	0	0	Potassium, K	0	0
Bromine, Br	0.091	0	Praseodymium, Pr	0	0
Cadmium, Cd	0	0	Rhenium, Re	0	0
Caesium, Cs	0	0	Rubidium, Rd	0	0
Calcium, Ca	71.7	431.0	Ruthenium, Ru	0.028	0.035
Cerium, Ce	1.754	11.270	Samarium, Sm	0.134	0.329
Chlorine, Cl	30.9	6.7	Scandium, Sc	0.026	0.094
Chromium, Cr	0.801	3570	Selenium, Se	0	0
Cobalt, Co	0.016	2.552	Silicon, Si	72,600	44,800
Copper, Cu	0	108	Silver, Ag	0	0
Dysprosium, Dy	0.222	268.9	Sodium, Na	224	1,208
Europium, Eu	0.026	0.0528	Strontium, Sr	0	0
Gallium, Ga	23.5	127	Tantalum, Ta	0	0.050
Gold, Au	0.009	0.016	Tellurium, Te	0	2.060
Hafnium, Hf	0.592	651.4	Terbium, Tb	0.010	0.119
Holmium, Ho	0	0	Thorium, Th	0.099	2.485
Indium, In	0	0	Thulium, Tm	0	0
Iridium, Ir	0	0	Tin, Sn	0	0
Iron, Fe	17.0	3,056	Titanium, Ti	144	546
Lanthanium, La	1.022	2.422	Tungsten, W	0	0
Lutetium, Lu	0.004	0.934	Uranium, U	0.055	3.013
Magnesium, Mg	0	494	Vanadium, V	0	57.3
Manganese, Mn	1.09	135	Ytterbium, Yb	0.033	3.451
Mercury, Hg	0	0	Zinc, Zn	0	0
Molybdenum, Mo	0	0	Zirconium, Zr	7.441	6880

* mg/kg. A zero indicates a value below detection limit (BDL).

TABLE 6: Chemical Elemental Analysis (Long Irradiation) of Fly Ash

Element	Quantity in PPM* Fly Ash F1	Element	Quantity in PPM* Fly Ash F1
Aluminum, Al	11,400	Neodymium, Nd	2.900
Antimony, Sb	0.269	Nickel, Ni	0
Arsenic, As	0.422	Osmium, Os	0
Barium, Ba	1626	Potassium, K	7,500
Bromine, Br	0	Praseodymium, Pr	0
Cadmium, Cd	0	Rhenium, Re	0
Caesium, Cs	1.196	Rubidium, Rb	16,860
Calcium, Ca	35,900	Ruthenium, Ru	1.925
Cerium, Ce	43,570	Samarium, Sm	12
Chlorine, Cl	0	Scandium, Sc	5.418
Chromium, Cr	22.76	Selenium, Se	0.333
Cobalt, Co	6.176	Silicon, Si	0
Copper, Cu	0	Silver, Ag	0
Dysprosium, Dy	5.260	Sodium, Na	17,730
Europium, Eu	0.627	Strontium, Sr	1,950
Gallium, Ga	296	Tantalum, Ta	0.608
Gold, Au	0	Tellurium, Te	1.524
Hafnium, Hf	9.402	Terbium, Tb	0.423
Holmium, Ho	0.996	Thorium, Th	9.489
Indium, In	0	Thulium, Tm	0
Iodine, I	4.0	Tin, Sn	0
Iridium, Ir	0	Titanium, Ti	5,610
Iron, Fe	11,150	Tungsten, W	0
Lanthanium, La	26,150	Uranium, U	2.545
Lutetium, Lu	0.249	Vanadium, V	205
Magnesium, Mg	4,170	Ytterbium, Yb	1.840
Manganese, Mn	99	Zinc, Zn	0
Mercury, Hg	0	Zirconium, Zr	181.7
Molybdenum, Mo	2.516		

* mg/kg. A zero indicates a value below detection limit (BDL).

TABLE 7: Leachate Analysis of CLSM Ingredients

Parameter	Clean Foundry Sand, FS1 (mg/l)	Used Foundry Sand, FS2 (mg/l)	Fly Ash F2 (mg/l)	Drinking Water Standards (mg/l)	GWQS*	
					Enforcement Limit (mg/l)	Preventive Action Limit (mg/l)
Aluminum	0.06	0.58	1.9		-	-
Antimony	0	0	0		-	-
Boron	0.006	0.018	9.1		-	-
Cobalt	0	0	0		-	-
Iron	0.02	0.93	0		0.30**	0.15**
Nickel	0	0.02	0		-	-
Potassium	0	41	20		-	-
Barium	0.013	0.053	0.12	1.0	2.0**	0.4**
Calcium	0.41	0.44	230		-	-
Magnesium	0.08	0.08	5.3		-	-
Manganese	0	0.01	0		0.05**	0.025**
Molybdenum	0	0	0.45		-	-
Silica	0.3	0.87	0.61		-	-
Sodium	0.23	1.7	32		-	-
Zinc	0	0.03	0		5**	2.5**
Arsenic	0	0.001	0.074	0.05	0.05	0.005
Chromium	0	0.011	0.051	0.05	0.10	0.01
Lead	0	0.015	0	0.05	0.015	.0015
Selenium	0	0	0.014	0.01	0.05	0.01
Cadmium	0	0.0002	0	0.01	0.005	0.0005
Mercury	0	0	0		0.002	0.0002
pH at 25° C	4.1	6.1	8.7		-	-
Chloride	0	3	0		250**	125**
Conductivity at 25° C (i Mho)	53	147	1183		-	-
Sulfate	0	0	600		-	-
Alkalinity as CaCO3	0	100	59		-	-
Total Dissolved Solids	42	92	988		-	-
Total Hardness as CaCO3	0	0	600		-	-
Total Phosphorus	0.04	0.2	0.16		-	-

Note: A zero indicates a value below detection limit (BDL)

* GWQS = Groundwater Quality Standard (Public Health-Related)

** GWQS related to public welfare.

TABLE 8: Leachate Characteristics of Fly Ash F1 Mixtures with and without Foundry Sand

Parameter	S1-2(P) (mg/l)	S4-2(P) (mg/l)	S7-2(P) (mg/l)	S8-2(P) (mg/l)	S9-2(P) (mg/l)	Drinking Water Standards (mg/l)	GWQS*	
							Enforcement Standard, (mg/l)	Prevention Action Limit, (mg/l)
Foundry Sand, (%)	0	70(FS1)	50(FS2)	70(FS2)	85(FS2)	-		
Aluminum	8.2	7.6	6.8	5.3	5.3			
Antimony	0	0	0	0	0			
Boron	0.065	0.053	0.065	0.062	0.034			
Cobalt	0	0	0	0	0			
Iron	0	0	0	0	0		0.30**	0.15**
Nickel	0	0	0	0	0			
Potassium	12	6.6	9.3	13	13			
Barium	0.79	0.43	0.88	0.62	0.48	1.0	2.0**	0.4**
Calcium	100	88	120	89	90			
Magnesium	0	0	0	0	0		0.05**	0.025**
Manganese	0	0	0	0	0			
Molybdenum	0.13	0	0.09	0.13	0.06			
Silica	3	3.5	3.1	4.3	4			
Sodium	8.1	4	3.7	3.6	3.4			
Zinc	0	0	0	0	0		5**	2.5**
Arsenic	0	0	0	0	0	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	0	0	0	0	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	0	0	0	0	0.01	0.005	0.0005
Mercury	0	0	0	0	0		0.002	0.0002
pH at 25° C	11.3	11.4	11.3	11.2	11.2			
Chloride	0	0	0	1	1		250**	125**
Conductivity at 25° C (i Mho)	1150	852	1154	886	887			
Sulfate	20	20	16	14	14			
Alkalinity as CaCO ₃	290	220	280	230	210			
Total Dissolved Solids	324	256	354	255	278			
Total Hardness as CaCO ₃	250	220	300	222	225			
Total Phosphorus	0.03	0.02	0	0	0.02			

Note: A zero indicates a value below detection limit (BDL)
 * GWQS = Ground Water Quality Standard (Public Health-Related)
 ** GWQS related to public welfare.
 FS1 = Clean Foundry Sand.
 FS2 = Used Foundry Sand.

TABLE 9: Leachate Characteristics of Fly Ash F2 Mixtures with and without Foundry Sand

Parameter	P1-8(P) (mg/l)	P3-2(P) (mg/l)	P6-2(P) (mg/l)	P8-2(P) (mg/l)	P9-2(P) (mg/l)	Drinking Water Standards (mg/l)	GWQS*	
							Enforcement Standard, (mg/l)	Preventive Action Limit, (mg/l)
Foundry Sand, %	0	50(FS1)	30(FS2)	70(FS2)	85(FS2)	-		
Aluminum	3.2	2.6	5.1	3.8	5.2			
Antimony	0	0	0	0	0			
Boron	1.2	2	1.3	0.82	0.45			
Cobalt	0	0	0	0	0			
Iron	0	0	0	0	0		0.3**	0.15**
Nickel	0	0	0	0	0			
Potassium	14	19	20	16	3.4			
Barium	0.039	0.037	0.011	0.018	0.081	1.0	2.0**	0.4**
Calcium	49	68	49	51	85			
Magnesium	0.28	0.58	0.21	0.07	0			
Manganese	0	0	0	0	0		0.05**	0.025**
Molybdenum	0.05	0.17	0.08	0	0.05			
Silica	4.2	3.5	3.4	4.5	3.8			
Sodium	9	13	10	3.6	0.7			
Zinc	0	0	0	0	0		5**	2.5**
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	0	0	0	0	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	0	0	0	0	0.01	0.005	0.0005
Mercury	0	0	0	0	0		0.002	0.0002
pH at 25° C	10.5	10.2	11.4	9.5	11.4			
Chloride	0	0	0	0	0		250**	125**
Conductivity at 25° C (i Mho)	383	482	464	338	754			
Sulfate	84	140	140	56	37			
Alkalinity as CaCO ₃	79	80	93	46	180			
Total Dissolved Solids	230	314	232	254	260			
Total Hardness as CaCO ₃	120	170	120	130	210			
Total Phosphorus	0.03	0.04	0.03	0.03	0.02			

Note: A zero indicates a value below detection limit (BDL)

* GWQS = Groundwater Quality Standard (Public Welfare-Related)

** GWQS related to public welfare.

FS1 = Clean Foundry Sand

FS2 = Used Foundry Sand